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Executive
Summary

December 1971

Preliminary
Design of a
Shuttle Docking
and Cargo
Handling System

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Final Report, Executive Summary

December 1971

**PRELIMINARY DESIGN
OF A SHUTTLE DOCKING
AND CARGO HANDLING
SYSTEM**

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FOREWORD

This document presents a summary of the work performed by the Martin Marietta Corporation's Denver Division while under contract to NASA Manned Spacecraft Center. This summary report was prepared as partial fulfillment of Contract NAS9-11932, *Preliminary Design of a Shuttle Docking and Cargo Handling System*. The NASA Technical Monitor for the Contract was Mr. Richard B. Davidson, of the Spacecraft Design Office, Engineering Technology Branch.

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I. INTRODUCTION

The objective of this study was the preliminary design of a Shuttle docking and cargo handling system. This report presents a summary of the work conducted during the study program. The first three chapters of the report following the Introduction and Summary represent the work performed prior to concept selection, and include (1) the requirements and guidelines used to formulate concepts, (2) analysis performed to determine detailed requirements for reach, velocity, torque, etc., (3) the formulation of the alternative concepts, (4) the evaluation and ranking of these concepts, and (5) the selection of a concept. Chapter VI summarizes the man-in-the-loop simulations performed with a six degree of freedom moving base simulator and a three degree of freedom manipulator arm. In Chapter VII, we present the analysis and tradeoffs of those design parameters which are the key to the preliminary design, described in Chapter VIII. Chapter VIII is divided into subsystem sections. Chapter IX presents our estimates for a future development program and includes a schedule and manpower breakdown and cost estimate. A summary of the system design parameters including a weight and power breakdown and estimate is included in Chapter X. In addition, this Chapter enumerates those areas that require further analysis and tradeoffs.

II. SUMMARY

Requirements - The preliminary design of a Shuttle-attached remote manipulator system (RMS) is based on an arm that is articulated at shoulder, elbow, and wrist. This arm enables the RMS to perform the following tasks: (1) "capturing" orbital payloads such as the Space Station, satellite, or a disabled Shuttle; (2) docking the Shuttle to orbital payloads, such as the Space Station, manned module, or a disabled Shuttle; (3) unload and deploy cargo from the Shuttle cargo bay; (4) unloading Space Station module from Shuttle, transfer and dock module to Space Station; and (5) assembling orbital payloads. Mission derivable requirements and design guidelines were established. These include operational time lines, minimum and maximum payloads, minimum arm reach, precontact and postcontact velocities, arm tip velocities and accelerations, etc.

A preliminary requirement analysis was conducted, and the significant results of this work were parametric design sensitivity curves relating arm reach, torque required, Shuttle attachment point, joint weight, and beam weight. From these curves penalties in arm weight were determined as other parameters were varied. Significantly, there was very little or no weight difference for arms between 9.1 m (30 ft) and 18.3 m (60 ft) long. Typically, torque requirements were 3500 N-m (2500 ft-lb) for docking the Shuttle to the Space Station in 10 minutes and 176.8 N-m (130 ft-lb) for unloading and deploying a 29,400 kg (65,000 lb) payload in 10 minutes.

Concept evaluation and Selection - Forty-two alternative concepts were formulated and screened to provide ten concepts. These were conceptually designed, evaluated, and ranked. The evaluation considered 20 comparative parameters, including development risk, Shuttle interface, crew work load, mechanical complexity, fail-operational capability, etc. A two-arm 15.3 m (50 ft) fixed length, fixed base concept was selected.

Simulations - Man-in-the-loop simulations were performed with 2.1 m (7 ft) manipulator arms and a TV system. The simulation investigated the controllability of manipulator arms. Both rotational hand controllers (joy stick) and a geometrically similar master were used for slave control. The simulations verified the feasibility of a Shuttle RMS for capturing moving targets.

Requirements Analysis - Detailed requirements analysis was carried out on the selected concept with emphasis on specific requirements for 14 system parameters: arm length, joint positional accuracy, joint rate accuracy, control methods, degrees of freedom, gimbal ordering, joint angular velocity, joint torques, reach envelope, joint angular travel, command and data link, tracking and ranging, arm deployment, and ground testing. The system characteristics analysis formed the basis for the RMS configuration.

System Description - A preliminary design of the RMS was established with emphasis on six subsystem areas: mechanical, structural, control, dynamics, crew systems and man/machine interface, and telecommunications. The system is described in the following paragraphs.

The RMS consists of two identical manipulator arms mounted near the forward bulkhead of the Shuttle Orbiter cargo bay as illustrated in Fig. II-1. The arms are designed so that only one arm is required to accomplish all tasks associated with capture, docking, and cargo handling operations. Thus, the RMS is redundant, in that if either arm fails, the other arm can be used to perform all required tasks except orbital assembly where two arms are needed.

The total arm length is 15.3 m (50 ft) long. The shoulder-to-elbow segment is 7.15 m (23.5 ft) and is equal to the elbow-to-wrist segment. The wrist extension makes the terminal device 0.9 m (3.0 ft) from the wrist. The arm diameter is such that each can be stowed in an envelope approximately 20.3 cm (8 in) diameter by 15.3 m (50 ft) long. The deployment device places the shoulders 6.1 m (20 ft) apart for improved reach envelope. The weight of one arm and deployment mechanism is about 544.8 kg (1200 lb). Total RMS weight including aluminum arms, terminal device, four TV cameras, lights, deployment devices, complete control console, and control and data electronics is estimated at 1264 kg (2783 lb). This weight reduces to 619 kg (1364 lb) if Lockalloy replaces aluminum for the arm. The arm is designed for a maximum tip force of 44.5 N (10 lb) and for a maximum tip deflection of 2.54 cm (1.0 in).

Each arm has a total of eight degrees of freedom: shoulder, two (pitch and yaw); elbow, two (roll and yaw); wrist, three (yaw, pitch, and roll); and terminal device, one. Joint accuracy provides for a tip positional error accuracy of ± 5.1 cm (2 in) and a tip velocity error of ± 1.5 cm/sec (0.05 ft/sec).

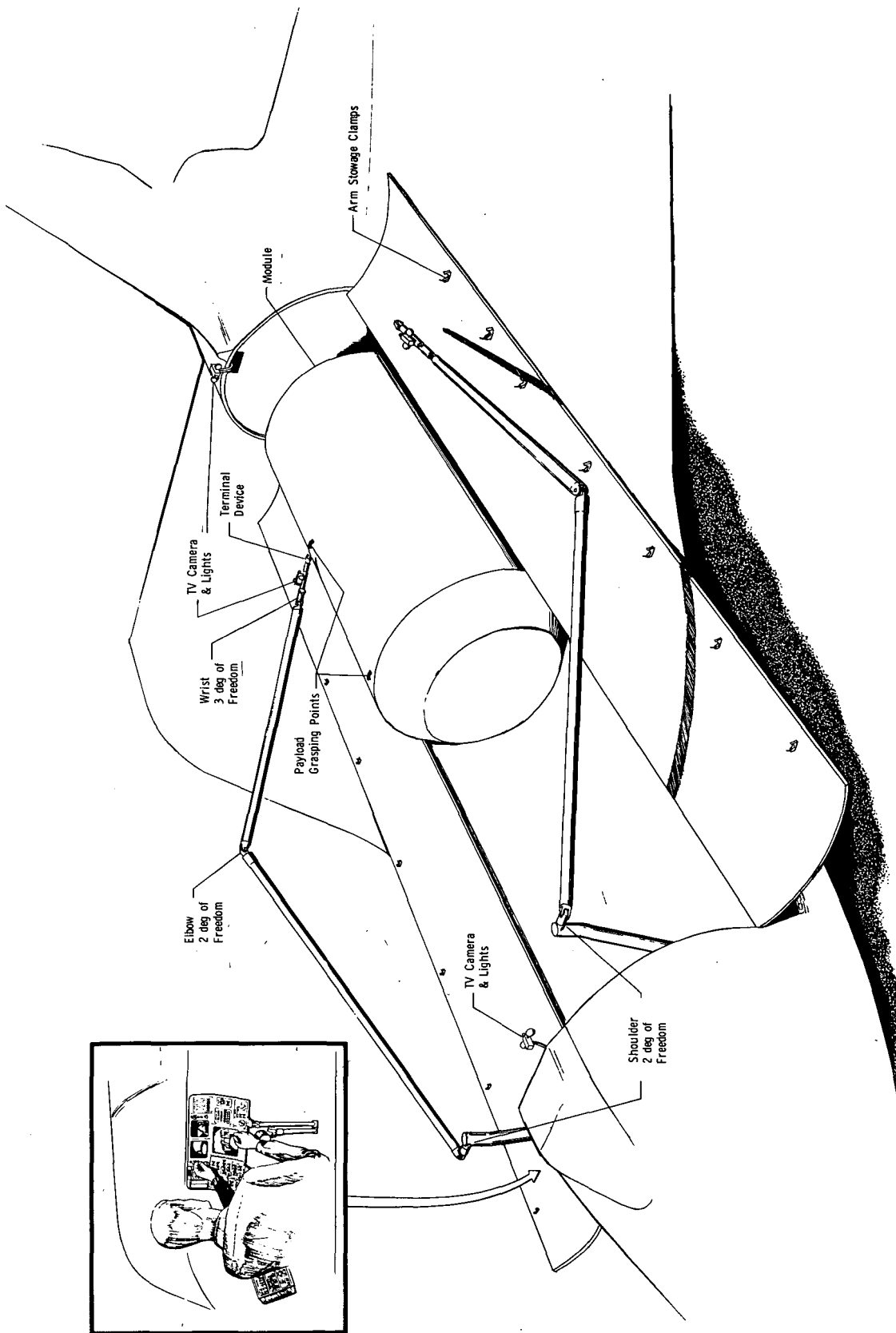


Fig. II-1 Shuttle Remote Manipulator System

Viewing for RMS operations is provided by direct viewing capability from the Shuttle cockpit, supplemented by four monoscopic TV cameras, each with two attached floodlights. The base mounted TV camera automatically follows the terminal device.

The RMS control system incorporates force feedback to allow the operator to feel the contact forces and moments. The input controller consists of either a geometrically similar master controller, a six-degree-of-freedom handcontroller, or two three-degree-of-freedom hand controllers. For analysis purposes, the master arm controller was assumed, since it presents somewhat higher requirements from the standpoint of crew cabin volume and control logic. The control system has four basic modes of operation: (1) manual control with low sensitivity for positioning the arm in the general vicinity of the desired area; (2) manual control with high sensitivity for five manipulations; (3) computer augmentation for indexing and coordinate transformation requirements; and (4) computer programmed automatic control for predetermined tasks such as arm deployment and cargo transfer. The RMS is designed to be controlled by a single crewman.

The RMS is designed for maximum cargo payload of 29,400 kg (65,000 lb) and designed for docking with a Space Station or another 145,280 kg (320,000 lb) orbiter. For the docking operation, the arm, after capturing the payload, is used as a sensor to provide accurate position and velocity information to the Shuttle RCS thrusters. After the initial relative velocity between the Shuttle and Space Station is reduced to 0.03 m/sec (0.1 ft/sec), the arm can be used to supply the forces to reduce relative velocities to zero and bring the two spacecraft together for mechanical locking. The latter two operations can also be done using the arm as a sensor to provide precise information for controlling the Shuttle RCS for docking operations. Figure II-2 is a block diagram representation of the RMS system,

Many tasks other than those presently required can be accomplished with the RMS. The Large Space Telescope (LST) is an example of where capture and then holding of the LST can be done with one arm while performing maintenance and module replacement tasks with the other arm. Other satellite retrieval tasks with specially designed terminal devices also become feasible RMS tasks.

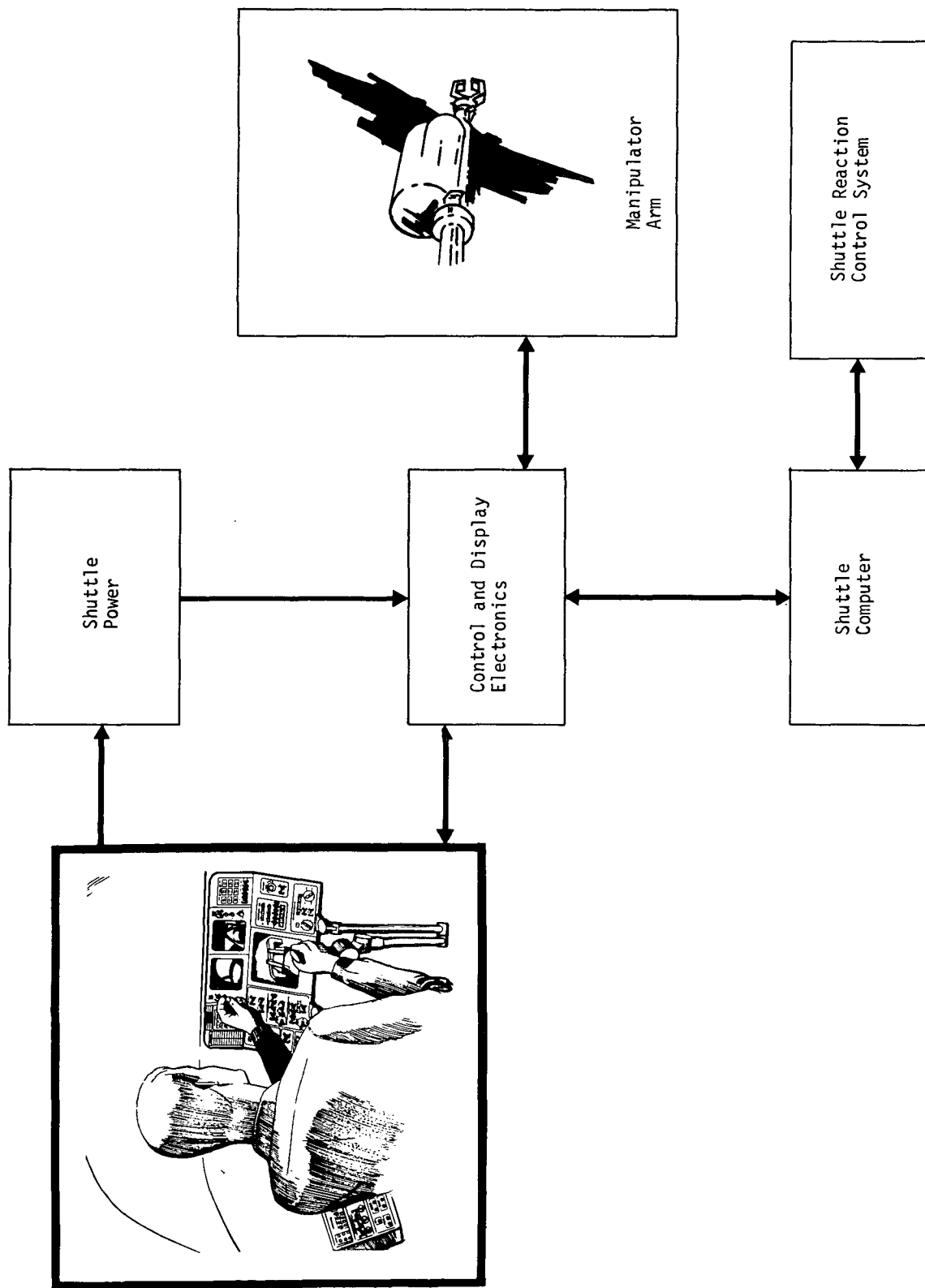


Fig. II-2 Remote Manipulator System Block Diagram

III. RMS REQUIREMENTS

The Shuttle Remote Manipulator System (RMS) requirements are based on manipulator arm(s) attached to the Shuttle Orbiter. For analysis purposes, the baseline Orbiter is the McDonnell Douglas design with cargo erection device removed and with docking port placed forward of the cockpit. The primary requirements are performance characteristics and physical characteristics. The requirements are categorized as Mission Derivable Requirements, and Design Guidelines. A summary of the critical requirements are presented in the following paragraphs.

1. Operational Requirements

The matrix shown in Table III-1 lists the primary tasks to be performed by the manipulator system. In addition, all inverse tasks (such as capture and load cargo) are also to be performed. For all tasks, the manipulator system provides all power and control for task accomplishment.

Table III-1 RMS Operational Requirements

RMS FUNCTION	1. SPACE STATION	2. SPACE STATION MODULE (20,000 LB)	3. MAXIMUM ORBITER PAYLOAD (65,000 LB)	4. 2270 kg (5000 lb) SATELLITE	5. 182 kg (400 lb) SATELLITE	6. DISABLED SHUTTLE ORBITER
A. PRE-CAPTURE (Deploy Arms to Ready Position)	▲	▲	▲	▲	▲	▲
B. CAPTURE (Mechanically Couple) (Terminal Device & Object)	▲	▲	▲	▲	▲	▲
C. DOCK SHUTTLE TO ORBITING OBJECT.	▲	▲				▲
D. UNLOAD AND DEPLOY CARGO FROM SHUTTLE CARGO BAY.		▲	▲	▲	▲	
E. MODULE UNLOAD, TRANSFER, AND DOCK TO SPACE STATION.		▲				

2. Payload Characteristics

The physical characteristics of the payloads to be handled by the manipulator system range from a 0.6 m (2 ft) diameter by 1.2 m (4 ft) length satellite weighting 182 kg (400 lb) to a 4.6 m (15 ft) diameter by 18.3 m (60 ft) length cargo module weighing 29,400 kg (65,000 lb). In addition, the RMS must handle a 76,000 kg (168,400 lb) Space Station or another 145,000 kg (320,500 lb) Shuttle Orbiter for docking operations.

3. Reach Envelope

The manipulator extension shall be adequate to reach any cargo in any location in the Shuttle cargo bay payload envelope. The reach distance shall be considered unobstructed from the manipulator base to the terminal device and shall be adequate to accomplish the docking and module transfer tasks.

4. Stowage and Deployment

The manipulator system shall be stowed in a manner acceptable for launch, orbit, and reentry of the Shuttle Orbiter. The stowage technique shall not significantly affect the Shuttle thermal protection system. The system shall be deployed from its stowed position by remote control from the manipulator control station.

5. Operations and Monitoring

The manipulator system shall be operated and monitored by a single Shuttle crewmember from a control and display station to be located in the Shuttle Orbiter. All computational requirements associated with normal operation shall be performed on-board the Shuttle. The system shall include illumination for the tasks to be performed.

6. Precontact Dynamics

The system design shall consider the following Shuttle docking closure rates and misalignments: forward velocity 0.1219 m/sec (0.4 ft/sec); lateral velocity 0.0475 m/sec (0.15 ft/sec); centerline miss distance ± 0.1524 m (6 in); angular rate 0.1 deg/sec; angular error ± 3.0 deg.

7. Viewing

Baseline viewing shall be accomplished by means of direct viewing supplemented by remote controlled television cameras.

8. Docking Port Contact Dynamics

The system shall control the Shuttle docking such that the following maximum docking port contact conditions shall be met:

Lateral alignment	± 0.051 m (± 2 in)
Angular alignment	± 1 deg
Closing velocity	± 0.0305 m/sec (± 0.1 ft/sec)
Lateral velocity	± 0.0152 m/sec (0.05 ft/sec)
Angular velocity	0.05 deg/sec

9. Response Characteristics

The speed, acceleration, and accuracy characteristics of the system shall be such that the RMS tasks can be performed in the maximum times shown in the tabulation.

	Time (min)
Task A. Precapture	3
Task B. Capture	2
Task C. Dock Shuttle	10
Task D. Unload and Deploy Cargo	10
Task E. Module Unload, Transfer and Dock to Station	10

IV. PRELIMINARY REQUIREMENTS ANALYSIS

The preliminary requirements analysis consisted of transcribing the RMS requirements of Chapter III into meaningful manipulator design parameters. The objective was twofold: (1) to provide a logical basis for formulating the alternative manipulator concepts, and (2) to provide the data for evaluating the concepts. The requirements for the task operations, their timelines, the precontact and postcontact velocity and misalignments, and the masses, inertias and dimensions of the principals were developed. From these the design criteria for arm tip velocities and accelerations, arm lengths, docking and cargo handling torques, arm joint parameters, docking and cargo handling beam parameters, and electrical power were derived.

A. REACH REQUIREMENTS

This requirements is dictated by the geometry of the tasks to be performed and the arm attachment point on the Shuttle. Five reach points were considered: (A) Shuttle docking port; (B) Space Station module (near-side) docking port; (C) Space Station module (far-side) docking port; (D) Shuttle cargo bay, forward lower point; and (E) Shuttle cargo bay, rear lower point.

Next it was assumed that the RMS arms would be attached to the Shuttle in its symmetry plane somewhere between the nose and the tail on or near the top surface. A simple digital computer program was written to calculate the distance from points along the attachment line to each of the reach points (A, B, C, D, E). The resulting data with corresponding letters have been plotted and are shown in Fig. IV-1. A matching Shuttle silhouette is shown above the curves. The C reach requirement is eliminated with the operational solution of docking the Shuttle in the opposite direction.

Examining the curves in this figure it can be seen that the minimum length for a single fixed base arm is one mounted at x-station 3226 cm (1270 in.) and has a length of approximately 14.6 m (48 ft). From these curves one also concludes that there is no arm length reduction by mounting the arm(s) forward of the docking port [x-station 2032 cm (800 in.)].

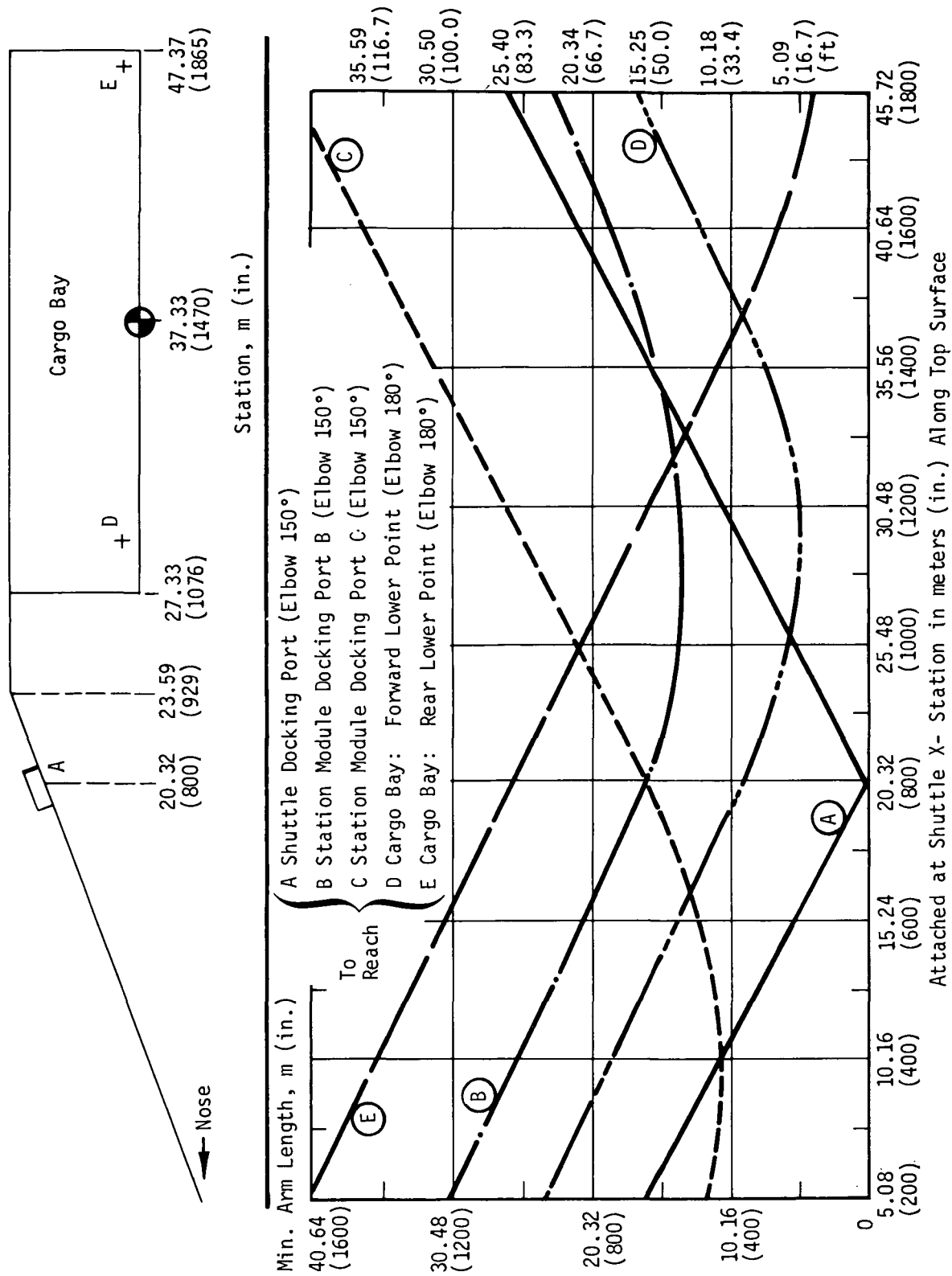


Fig. IV-1 Minimum Arm Length vs Attachment Point for Each Reach Point

B. VELOCITY AND ACCELERATION REQUIREMENTS

The requirements for accelerating or decelerating a load attached to the arm(s) is one of the most significant design parameters of the RMS. It determines the forces produced on the arm(s), and consequently the actuator torque and arm structure.

Four RMS tasks were individually analyzed and an approximate timeline established for each. The total time allowed for each task (given in Chapter III) was divided between the functions of that task. The maximum velocity and acceleration (or deceleration) was calculated where applicable for each function. These data are shown in Table IV-1.

C. TORQUE REQUIREMENTS

The torque requirements for both docking and cargo handling tasks were determined as a function of arm length.

The docking torque vs arm length curves (Fig. IV-2) show the increasingly high penalty paid in torque required for reducing the arm length. Increased torque (short arm length) means increased joint actuator weight and increased electrical power. The longer arm length that comes with decreased torque produces arm structural weight penalties and stowage problems. The variation in torque as a function of the attachment point shown in the curves was expected. As we move away from the center of mass the torque needed increases.

Next, the cargo handling torque requirements are examined. Four payloads are considered: (1) 181.6 kg (400 lb) satellite, (2) 2270 kg (5000 lb) satellite, (3) 9080 kg (20,000 lb) module, and (4) 29,510 kg (65,000 lb) module. Payloads (1), (2), and (4) are analyzed using the unload and deploy task while (3) is analyzed for both the unload and deploy (Task D) and the unload, transfer, and dock (Task E). The results are shown in Fig. IV-3.

Table IV-1 Manipulator Arm Velocity and Acceleration Requirements

RMS Tasks and Functions	Distance or Angle to Travel or Rate to Achieve	Estimated Time	V _{MAX} (tangential velocity at tip or angular rate of tip) m/sec (ft/sec)	A _{MAX} (tangential acceleration at tip) m/sec ² (ft/sec ²)
A. PRECAPTURE (Cargo doors open) Translate tip to "ready" position	16.47 m (54 ft)	1.5 min	0.18 (0.60)	0.11 (0.36)
	Total Time	1.5 min		
B. CAPTURE				
1. Translate tip to compensate for lateral misalignments between Shuttle and object	0.3 m (1 ft)	5 sec	0.08 (0.27)	0.11 (0.36)
2. Achieve and maintain constant lateral velocity to compensate for lateral velocity between Shuttle and object	0.05 m/sec (0.15 ft/sec)	5 sec	0.04 (0.15)	0.009 (0.03)
3. Achieve and maintain constant (negative) radial velocity to compensate for closing velocity between Shuttle and object	0.12 m/sec (0.4 ft/sec)	5 sec	0.13 (0.43)	0.2 (0.08)
4. Decrease radial velocity of tip so that tip-to-receptacle relative velocity is 0.03 m/sec (0.1 ft/sec)	0.09 m/sec (0.3 ft/sec)	5 sec	0.1 (0.34)	0.006 (0.02)
5. Mechanically couple terminal device to receptacle on object	0.3 m (1 ft)	10 sec	0.13 (0.43)	0.003 (0.01)
	Total Time	30 sec		
C. DOCK SHUTTLE to (or undock Shuttle from) orbiting object				
1. Reduce (a) closing velocity, (b) relative lateral velocity, and (c) relative angular velocities to zero before the closing distance is less than 3.3 m (10 ft)	a. 0 ft/sec b. 0 ft/sec c. 0 deg/sec 12.20 m (40 ft) (typical)	3.5 min	a. 0.12 (0.4) b. 0.046 (0.15) c. 0.1 deg/sec	0.00061 (0.002) 0.0002287 (0.00075)
2. Bring the object and the vehicle together so that their docking ports are 0.61 m (2 ft) apart and all relative velocities are zero	7.32 (24 ft)	3.5 min	0.043 (0.132)	0.00036* (0.0012)
3. Position the two so that the docking ports are aligned to within maximum allowed values		2 min		
4. Bring the two together so that at contact the relative velocities and alignment are within the maximum allowed values		1 min	0.021 (0.066)	0.00034† (0.0011)
	Total Time	10 min		
D. UNLOAD AND DEPLOY (or Retrieve and Load) Cargo from (or into Shuttle Cargo Bay				
1. Translate tip so that tip to receptacle distance (on cargo) is 0.3 m (1 ft)	2.44 m (8 ft)	30 sec	0.08 (0.27)	0.11 (0.36)
2. Orient tip to match receptacle on cargo within maximum allowed misalignments		20 sec		
3. Translate tip so that mechanical coupling is achieved between tip and receptacle on cargo	0.305 m (1 ft)	10 sec	0.03 (0.10)	0.11 (0.36)
4. Move cargo upward out of bay until lowest point of cargo is above highest point of bay	4.88 m (16 ft)	3 min	0.053 (0.174)	0.000305 (0.001)
5. Move cargo away from Shuttle and stop	7.93 m (26 ft)	4 min	0.053 (0.174)	0.000305 (0.001)
6. Orient cargo in desired attitude		100 sec		
7. Release cargo		20 sec		
	Total Time	10 min		
E. MODULE UNLOAD, TRANSFER AND DOCK TO SPACE STATION (or undock module, transfer, and load into Shuttle)				
1. Translate tip so that tip to receptacle distance (on cargo) is 0.3 m (1 ft)	2.44 m (8 ft)	30 sec	0.08 (0.27)	0.109 (0.36)
2. Orient tip to match receptacle on cargo within maximum allowed misalignments		20 sec		
3. Translate tip so that mechanical coupling is achieved between tip and receptacle	0.3 m (1 ft)	10 sec	0.03 (0.10)	0.1098 (0.36)
4. Move cargo upward out of bay until lowest point of cargo is above highest point of bay	4.88 m (16 ft)	2.5 min	0.064 (0.21)	0.000436 (0.00143)
5. Move cargo from shuttle and stop when cargo docking port is 4 feet from docking port on space station	15.25 m (50 ft)	4 min	0.086 (0.28)	0.000793 (0.0026)
6. Align cargo so that lateral errors are within maximum limits		45 sec		
7. Orient cargo so that attitude errors are within maximum allowable limits		45 sec		
8. Dock cargo to Space Station with contact conditions within the maximum allowed values	1.22 m (4 ft)	40 sec	0.03 (0.10)	0.000762 (0.0025)
9. Release cargo		20 sec		
	Total Time	10 min		

*Minimum acceleration for this task. Full acceleration for 1.75 min and full deceleration for 1.75 min. Velocity is maximum attained.

†Minimum acceleration to move 0.61 m (2 ft) in 1 minute. Full acceleration total time. Velocity is maximum achieved at contact.

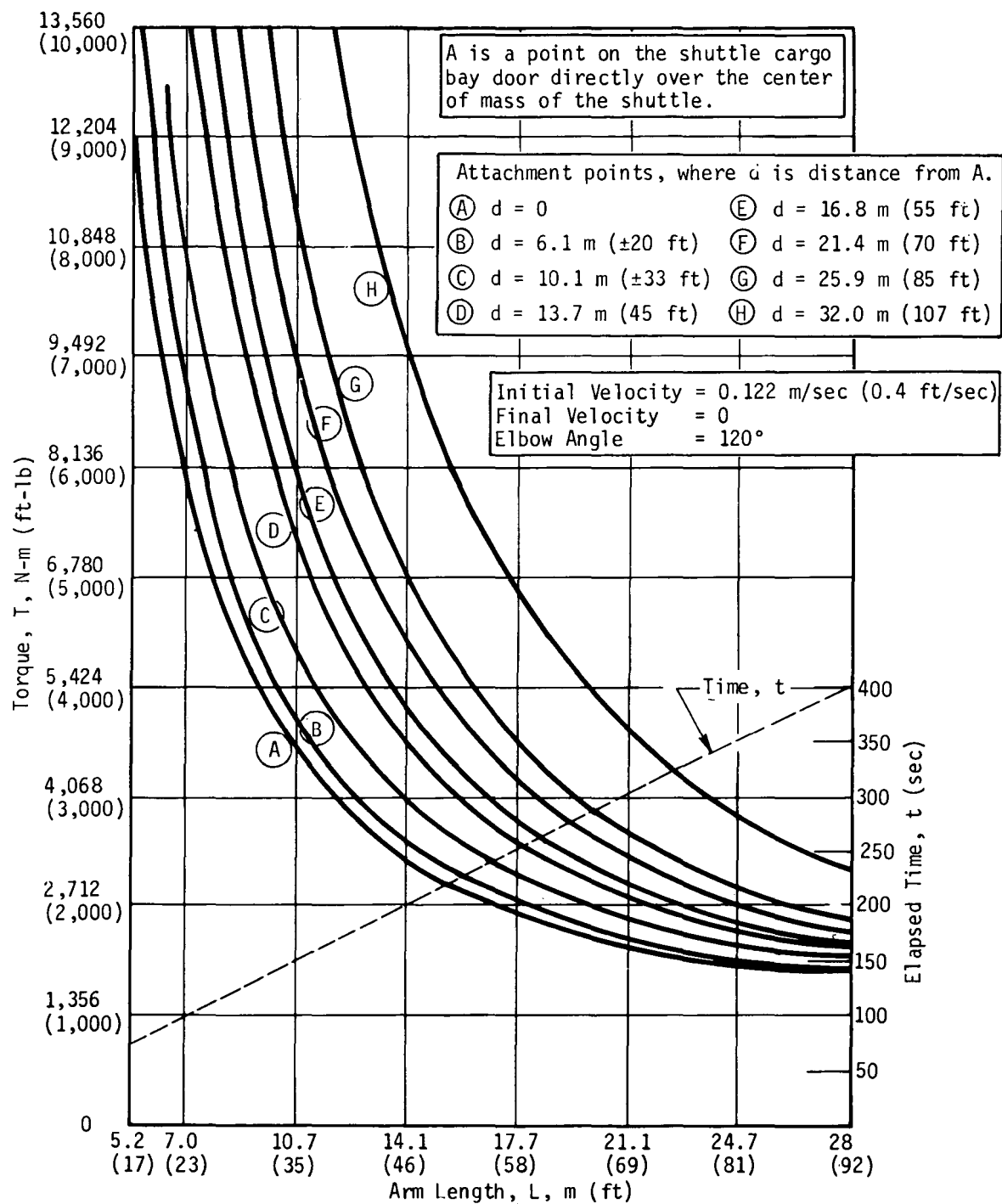


Fig. IV-2 Applied Torque and Elapsed Time vs Arm Length for Various Attachment Points: Swingby Case

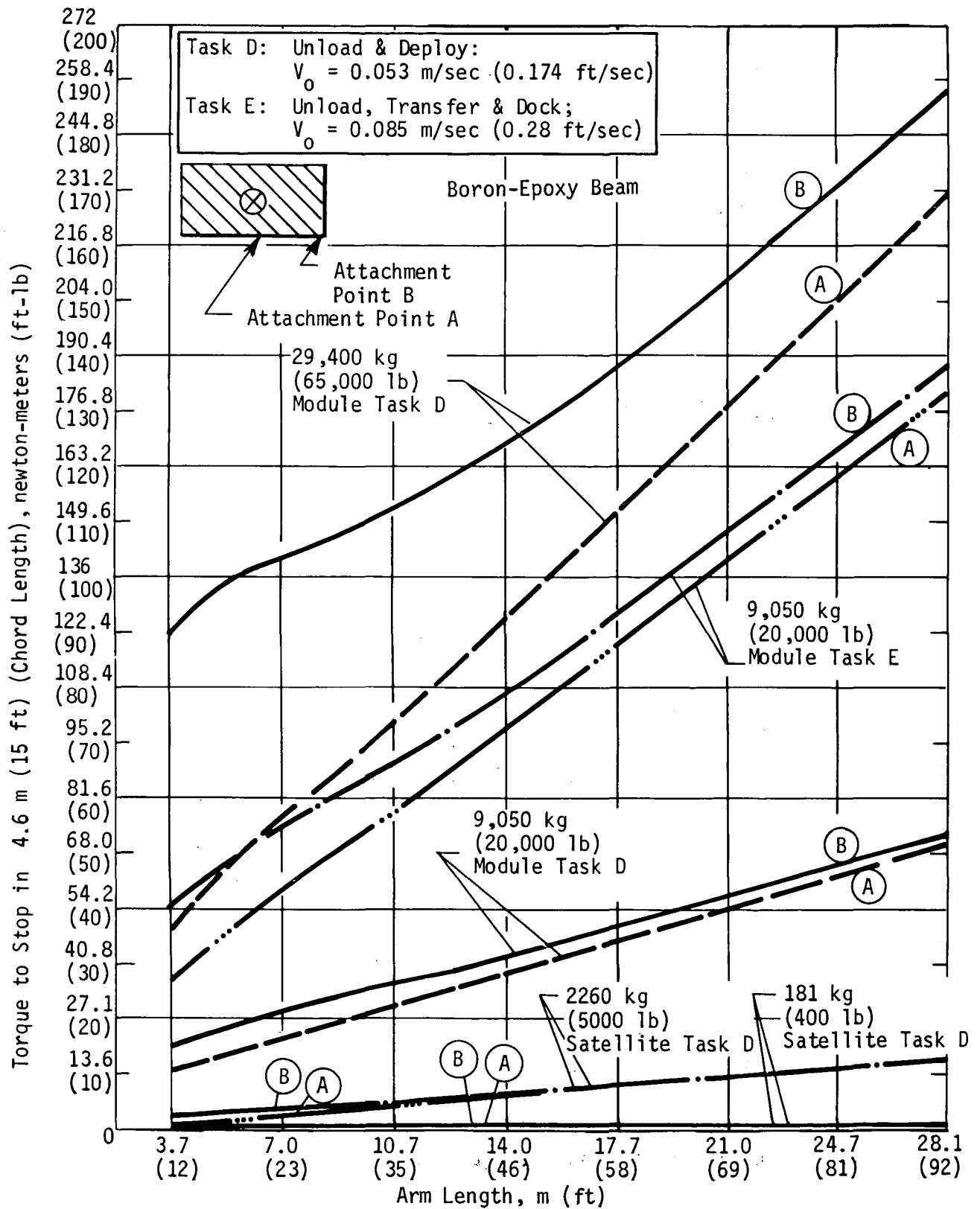


Fig. IV-3 Torque vs Arm Length to Stop Moving Cargo

D. JOINT WEIGHT AND BEAM WEIGHT

The torque requirements for docking, calculated in the preceding section and the velocity requirement established in Section B, were used to determine the motor and speed reducers necessary at each joint. For purposes of analysis a DC torque motor, a harmonic drive, and spur gears as required, were used as the basis for the joint actuation. Also for the purpose of alternative concept comparison it was assumed that only one arm was used.

The total joint weight was determined as a function of the required torque and added to the weight of the required arm beam. The resulting data revealed that for a large spectrum of arm lengths the total arm weight is constant. And for lengths from 7.02 m (23 ft) to 25.01 m (82 ft) the weight for all is between 136.2 kg (300 lb) and 181.6 kg (400 lb), using Boron-Epoxy for the beam material.

V. ALTERNATIVE CONCEPTS, EVALUATION, AND SELECTION

This chapter is the focal point for the study and analyses described in Chapters III and IV. The method of using the requirements to formulate and evaluate manipulator concepts is described in this chapter, which concludes with newly introduced requirements that affect the selection of a manipulator concept.

A. ALTERNATIVE CONCEPTS FORMULATION

Upon first examination, the variety of possible manipulator concepts seemed endless but engineering judgment was used to reduce the size of the problem. First, the possible Shuttle attachment points were narrowed down to include only the region from the forward cargo bay bulkhead to the rear bulkhead. The minimum reach requirements analysis and the stowage requirement helped substantiate this decision. Next, the multiplicity of arms was examined, and it was concluded that there was no justification for providing more than two manipulator arms. Thus, the number of alternative configurations was reduced significantly.

A total of 42 possible concepts, with one or two arms of fixed or variable length, and with one or more operating locations, (as shown in matrix form in Fig. V-1) were considered. Each of the 42 concepts shown in the matrix were examined individually. For attachment points near the forward cargo bay bulkhead, the need for increased reach capability was identified with the small light-weight payload located at the extreme end of the payload envelope. Other than providing a fixed length arm to reach this payload, an increased length capability could be provided by an additional arm at a different base, a variable length arm, or a moving base. The ground rules used were (1) only one means of increasing reach capability would be provided e.g., if the concept included a telescoping (variable length) arm, it would not also be provided with a moving base to accomplish the same objective; and (2) only one arm (for 2-arm concepts) will have increased reach capability by one of the methods described above. The matrix shows a geometric symbol coded entry for those concepts eliminated as possible candidates. The ten remaining candidates, coded A through J, are the concept types upon which the alternative configurations are based.

SELECTION FROM 42 POSSIBLE CONCEPTS						
Type of Operating Locations		One Fixed Operating Location		Several Variable Operating Locations		Several Fixed Operating Locations
Number of Arms ↓	Arm Length → Bases	Two Separate Bases		Two Separ. Bases (One Fixed)		Two Separ. Bases (One Fixed)
		One Base	One Base	One Base	One Base	One Base
1 Arm	Fixed	<i>A, I</i>	●	<i>C</i>	●	<i>F</i>
	Variable	<i>B</i>	●	▲	●	●
2 Ident. Arms (Size, Wt, Base, etc.)	Fixed	<i>D</i>	●	●	●	●
	Variable	●	●	▲	▲	▲
2 Non-Ident. Arms	Both Fixed	■	<i>E</i>	●	<i>H</i>	<i>J</i>
	Both Variable	●	●	▲	▲	▲
	One Fixed, One Variab.	<i>G</i>	▲	▲	▲	▲
<i>A, B, C, D, E, F, G, H, I, J</i> = Selected Alternative Concepts ● Not Applicable ■ No Advantage to Keep Both Arms at One Operating Location ▲ Redundant Means of Increasing Reach Capability ● Since need for increased reach capability is caused by the requirement to reach small (light) cargo, only one arm need have this capability. Also no need to have 2 identical arms if on separate bases.						

Fig. V-1 Selection from 42 Possible Concepts

B. CONCEPT EVALUATION

Each concept was evaluated from the standpoint of weight, arm functions, technology development status, complexity, and other parameters. In addition, a scale model of the Shuttle with attached manipulator arms was used to aid in the concept evaluation.

C. CONCEPT RANKING AND SELECTION

In ranking the concepts the advantages and disadvantages of each were compiled. The approach to the ranking was that the ideal concept has the least design complexity, interface problems, development cost, the best dynamic control, the most versatility, and the most redundancy, etc. A numerical approach to the ranking was carried out by six system and subsystem engineers with various weighting factors. All scoring methods yielded the same first-ranked concept: Concept A, one arm, fixed length, fixed base. The entire ranking, based on weighting (5, 3, 1) is shown in Table V-1.

Additional requirements were placed on the RMS; namely, that it be capable of the assembling two orbital payloads, for which two arms would be required. In addition, for all other tasks, only one arm would be used (either of the two arms). Relating to the concept ranking table, the selected concept became two of Concept A. The arms are structurally and mechanically designed so that all tasks (except orbital assembly) can be performed using only one arm. Thus, the concept has the operational and control simplicity of the one-arm concept and 100% redundancy on all tasks but one, which is an improvement over the two-arm concepts.

Further analysis of the Shuttle Traffic Model (July 1971) showed that stowage of the 227.0 kg (500 lb), 0.61 x 1.22 m (2 x 4 ft) satellite did not constrain it to the very end of the cargo bay payload envelope, and that it could be moved to a position near the cargo bay doors. Thus, the 181.6 kg (400 lb) satellite no longer was a severe driving force on the arm length requirement.

A change in emphasis was made from docking to cargo handling. The concept selected for further analysis was one whose strength and torque capabilities were determined by the cargo handling tasks.

Table V-1 Alternative Concepts Ranked

RANK	CONCEPT	SCORE	DESCRIPTION
1	A	216	One arm, fixed length, fixed base at cargo bay forward bulkhead.
2	I	227	One arm, fixed length, fixed base at 17 feet rearward from forward bulkhead.
3	D	254	Two arms, fixed length, fixed common base at cargo bay forward bulkhead.
4	B	272	One arm, telescoping length, fixed base at cargo bay forward bulkhead.
5	G	290	Two arms, fixed common base; one arm fixed length; other arm telescoping length, mounted at cargo bay forward bulkhead.
6	C	304	One arm, fixed length, moving base with primary position at cargo bay forward bulkhead.
7	H	325	Two arms, fixed length; one arm fixed base at forward bulkhead; other arm moving base with primary base at forward bulkhead.
8	E	354	Two arms, fixed length, fixed separate bases; one arm at cargo bay forward bulkhead; other arm at near bulkhead.
9	J	401	Two arms, fixed length; one arm fixed base; other arm movable base (self-locomotion) with primary position at forward bulkhead.
10	F	414	One arm, fixed length, movable base (self-locomotion) with primary base at cargo bay forward bulkhead.

The Shuttle reaction control system thrusters would be used to help reduce the relative velocities between the Shuttle and the Space Station (or other orbital payloads) after the RMS arm had been mechanically linked with the Space Station.

The stowage volume requirements was changed to approximately 8 inches diameter per arm so as to be more compatible with current Orbiter design concepts. In addition, aluminum was set as a design guideline material for the arms, and the weight requirement was relaxed to 910 to 1135 kg (2000 to 2500 lb).

VI. MAN-IN-THE-LOOP SIMULATIONS

Manipulator arm control problems were studied using the MMC Space Operations Simulator (SOS) supported by EAI 231R computers and a simplified control station mockup. The SOS has three rotational degrees of freedom obtained by an attitude head, and 3 translational degrees of freedom obtained by moving carriages. All 6 degrees of freedom are controlled by position servo drive systems and computer generated commands. The control station mockup consisted of a TV monitor and a chair from which the command input device was operated.

The hardware configuration in the SOS and the analog computer program were dependent on specific simulation objectives. Two separate configurations and computer programs, identified by Phase 1 and Phase 2, were used in the simulation studies.

For Phase 1, the manipulator arm was mathematically modeled in the computer. Inputs from the control device were used to calculate desired translational motion (in x, y or z direction) of the manipulator wrist. The computer then calculated how the manipulator arm shoulder and elbow joints must rotate to give the desired translational wrist motion, including effects of joint servo lags. Translational wrist position was then recalculated, added to the relative motion between Shuttle and Space Station module, and the resultant was applied to the 3 translational degrees of freedom of the SOS carriage. The SOS attitude head rotational commands were obtained by a combination of 3 degrees of relative rotational rates between the Shuttle and Space Station, the 2 degrees of terminal device of wrist joint rotation, and the shoulder and elbow arm angles. The simulated wrist joint was operated as a function of manual input commands (from hand or foot) and arm shoulder and elbow joint angles. The wrist motion calculated as a function of joint angles was such that the terminal device (and TV camera) did not rotate inertially as the arm was moved around. Its inertial rotation then was a function of only manual input commands.

The Phase 2 configuration consisted of the same scaled module mounted to the SOS attitude head, and actual scaled manipulator arms mounted to the support structure. The manipulator arms are scaled versions of space arms having two main segments each with the following characteristics:

- Segment length: 9.5 m (31 ft)
- 2 DOF at the shoulder: yaw and pitch
- 1 DOF at the elbow - pitch
- No mechanized wrist

The TV camera in Phase 2 was mounted at the base of the arms, giving more of a view of the arm and module mockup. The Phase 2 computer equations consisted of those required to calculate arm joint motions to give desired x, y, z, translational motions of the wrist (similar to Phase 1). The results were applied directly to the position servo systems driving each manipulator joint. Since the wrist joint was not mechanized, the probe was fixed in a given position. The TV camera was mounted on its own pan-tilt head and was operated from the foot controller at the operator's console. The module mockup, mounted to the attitude head, was driven relative to the arms at scaled relative velocities and rotational rates between the Shuttle and Space Station. An artist's concept of the Phase 2 Simulation Setup and associated information flow is shown in Fig. VI-1.

The specific task required of the operator in both Phases was to maneuver the probe into the receptacle of the docking port mockup, which was moving to simulate the precontact docking dynamics. Successful task completion occurred when the probe made contact with the receptacle; contact of the probe at any other point on the target was considered a failure. No postcontact dynamics were simulated and the probe and target were designed so that no damage occurred when contact was actually made. No manipulator arm structural vibration effects were included in the simulations.

The primary objectives of the simulations were to study the controllability and the difficulty of close-in maneuvering of a manipulator arm with a TV camera mounted either on the terminal device, or at the base of the arms.

Three types of control input devices were used in the simulation: (1) switch-box, (2) Apollo Block 1 rotational handcontroller, and (3) geometrically similar master arm. Both rate and acceleration control were used with the switch box and handcontroller, and position control with direct 1:1 angle tracking was used with the master arm. A rate bias capability was also incorporated into the control system to match the manipulator tip velocity to the main component of the fly-by velocity of the Space Station module.

The simulation was "flown" by five different operators, including two trained test pilots. Eight additional operators were used to control the master arm configuration in Phase 2. In all cases, the task proved to be feasible. The main problems encountered were lack of depth perception using the mono TV for viewing, and lack of knowledge of probe contact, since the simulation did not incorporate force-feedback into the control system. A summary of

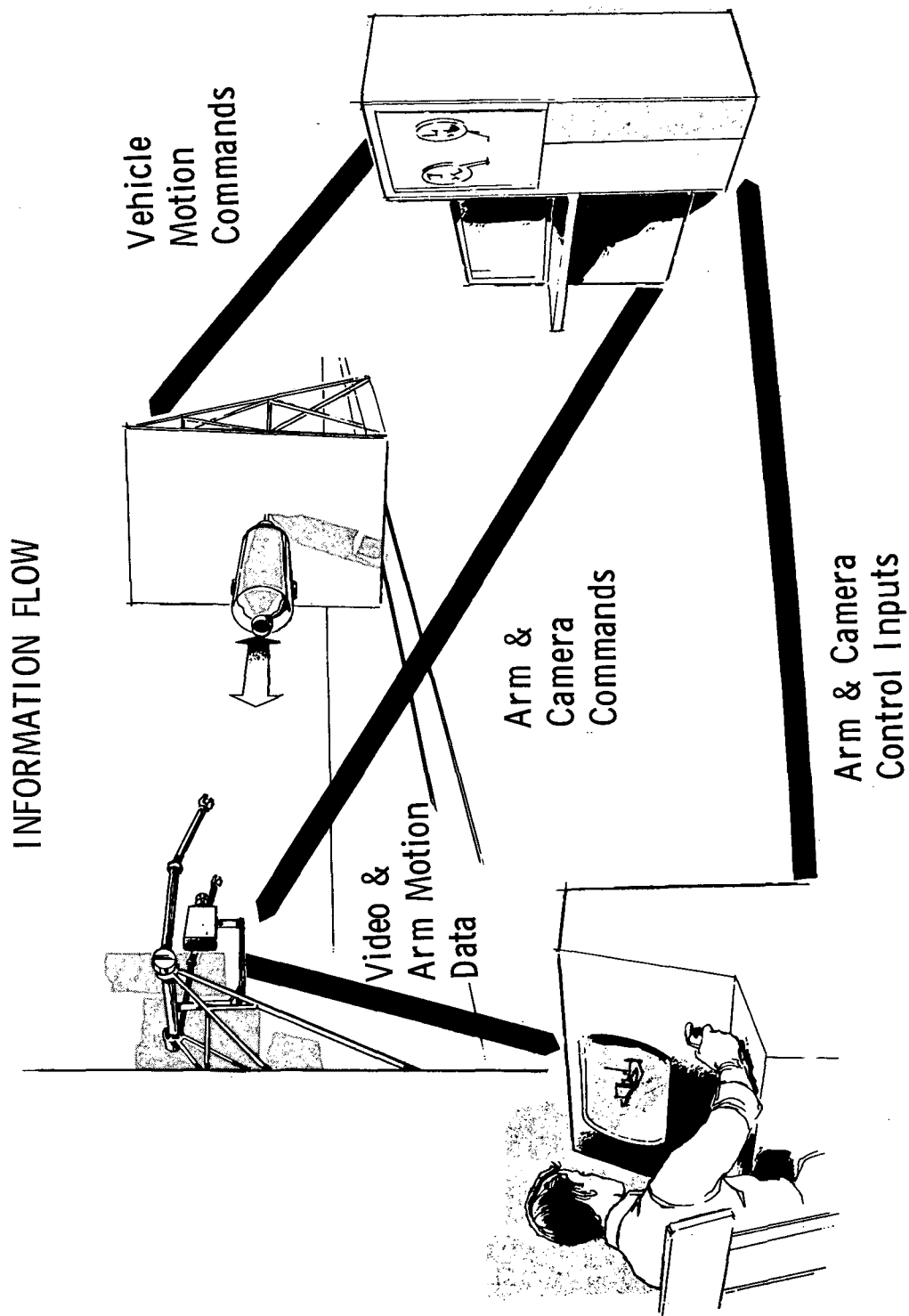


Fig. VI-1 RMS Simulator

the average times for task completion with the various control devices is given in Table VI-1.

Table VI-1 Summary of Average Task Times

	Phase 1				Phase 2				
	Hand Controller		Switch Box		Hand Controller		Switch Box		Master Arm
	Rate	Acc	Rate	Acc	Rate	Acc	Rate	Acc	Position
Total Average Time, sec	31	37	36	46	66	92	54	76	22

Independent of the input control device or control mode, the number of failures indicated that the task was still relatively difficult to accomplish. It was very difficult if not impossible to very closely match positions and velocities of the probe and receptacle at the same time. It was difficult enough to insert the 1.27 cm (0.5 in.) probe anywhere in the 5 cm (2 in.) receptacle without trying to insert it in the center of the receptacle. Final velocities at insertion ranged from near zero (not in all axes at once, however) to at least maximum relative Shuttle-Space Station velocities (say 0.015 m/sec, scaled). Phase 1 simulations also showed that it was very difficult to judge angular relationships between the probe and receptacle. Incorporation of depth perception cues and force-feedback to aid in the capture of the target would alleviate some of the problems associated with the capture task.

A summary of the conclusions reached follows.

- 1) The master-slave operating configuration was preferred over the hand controller or switch box. The master arm gave better control, faster operation, and took practically no time. This is partially attributable to the faster response and high sensitivity that was implemented with the master controller.
- 2) For hand-controller operation, the rate control mode and the use of TV camera control axes are recommended. Rate Bias is also recommended if information is available to implement it.

- 3) TV camera attitude control by foot is adequate.
- 4) The terminal device TV camera inertial attitude should be independent of manipulator arm motion.
- 5) Manipulator arm servo system time constants (lags) should not be greater than 1 second.
- 6) For the recommended control techniques and the capture task, task times should average from 0.5 to 1 minute.

VII. SELECTED CONCEPT REQUIREMENTS ANALYSES

The requirements analysis consisted of relating the general requirements presented in Chapter III to the specific manipulator configuration selected for the preliminary design. Requirements were established for 14 system parameters: arm length, velocity, torque, positional accuracy, rate accuracy, degrees of freedom, gimbal ordering, control method, reach envelope, angular travel, command and data link, tracking and ranging, deployment, and ground testing. The results of these analyses form the framework for the subsystem preliminary designs, described in Chapter VIII.

A. ARM PARAMETERS

The reach requirements were updated to include typical payloads derived from the NASA July 1971 Shuttle traffic mode. The total arm length was set at 14.3 m (47 ft), from shoulder to wrist, to reach the applicable small payloads, which the traffic model showed could be moved from the rear of the cargo bay. The linkage from wrist joint to the center of grasp of the terminal device was set to 0.9 m (3 ft) to allow for TV camera mounting and terminal device roll joint, as well as additional reach-around capability.

The relationship between the joint angles and the position of the wrist point was determined for a two-segment, typical three-degree-of-freedom arm. This relationship was then used to determine the positional and rate accuracy requirements necessary to maintain the wrist point position and velocity within particular limits. It was found that, for a segment length of 7.15 m (23.5 ft), a positional accuracy (of the wrist point) of ± 5.08 cm (± 2 in.) requires a joint accuracy of $\pm 1.97 \times 10^{-3}$ rad (± 0.113 deg), and a velocity accuracy of ± 0.015 m/sec (0.05 ft/sec) requires a joint rate accuracy of $\pm 5.82 \times 10^{-4}$ rad/sec (± 0.033 deg/sec).

The joint arrangement shown in Fig. VII-1 was selected for the preliminary design. This arrangement, which is similar to the human arm, consists of a Pitch-Yaw shoulder, a Roll-Yaw elbow, and a Yaw-Pitch-Roll wrist joint for angular orientation of the terminal device. This joint sequence was chosen for two prime reasons. First, it uses only one yoke-type joint at the elbow, which results in a minimum size elbow joint, and second, the elbow roll joint can be used to orient the TV camera in the best location for stowage. The three degree of freedom wrist shown allows angular orientation of the terminal device, and the TV location shown reduces the cable routing problems, since there is one less joint to route the TV cable around. The result is thus a 7 degree of freedom arm, with an eight degree of freedom for a hand-type terminal device.

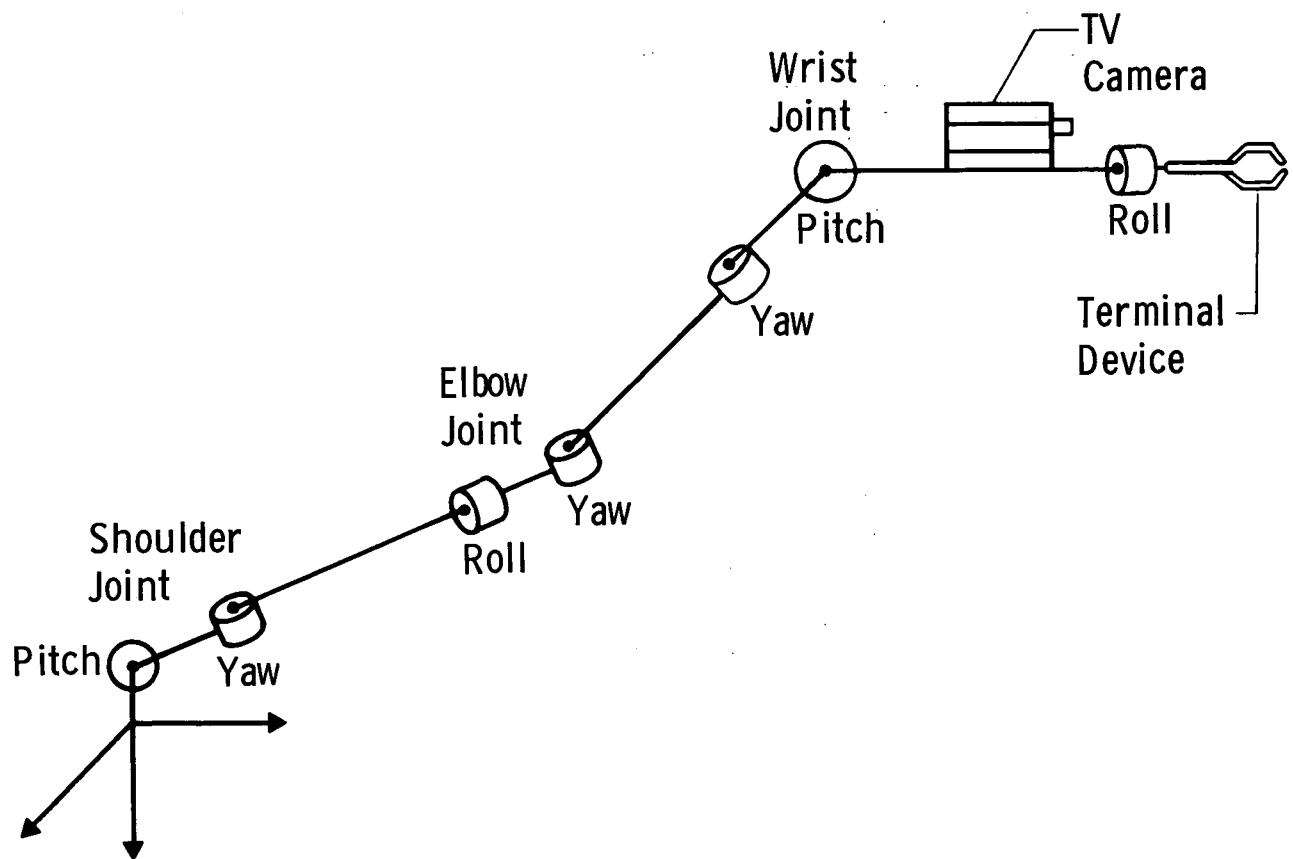


Fig. VII-1 RMS Joint Sequence

The 7 degree of freedom arm was chosen to allow independent elbow positioning for hazard avoidance, and to assure that full 6 degree of freedom motion of the arm could be obtained in any operating location.

The RMS torque and velocity requirements were derived primarily from the cargo handling requirements, with an additional no-load velocity requirement based on the capture task for docking and payload retrieval operations. Table VII-1 summarizes the joint velocities and torques necessary for accomplishment of the required tasks.

Table VII-1 Joint Velocity and Torque Summary

Shoulder: (pitch,yaw)	No-Load Velocity	0.03 rad/sec
	Full-Load Velocity	0.0035 rad/sec
	Torque Capability	667 N-m (500 ft-lb)
Elbow: (roll,yaw)	No-Load Velocity	0.0565 rad/sec
	Full-Load Velocity	0.0066 rad/sec
	Torque Capability	474 N-m (350 ft-lb)
Wrist: (yaw,pitch, roll)	No-Load Velocity	0.174 rad/sec
	Full-Load Velocity	0.0265 rad/sec
	Torque Capability	202 N-m (150 ft-lb) (Yaw, Pitch) 88 N-m (65 ft-lb) (Roll)

The required joint angular travel limits and the resulting reach envelope were also determined. The joint angular travel limits were derived from the reach requirements and the joint sequence of rotations determined previously. The analysis was based on wrist point reach and excludes additional reach produced by the wrist extension length of 0.9 m (3 ft). The result of this analysis was specification of the angular travel limits (Table VII-2) so that full volume coverage of the required work areas is obtained. A three dimensional view of the resulting reach envelope for one arm is shown in Fig. VII-2.

Table VII-2 Joint Angular Travel Limits

	Pitch	Yaw	Roll
Shoulder	+200°	+130°	NA
Elbow	NA	+155°	+200°
Wrist	+120°	+120°	+200°

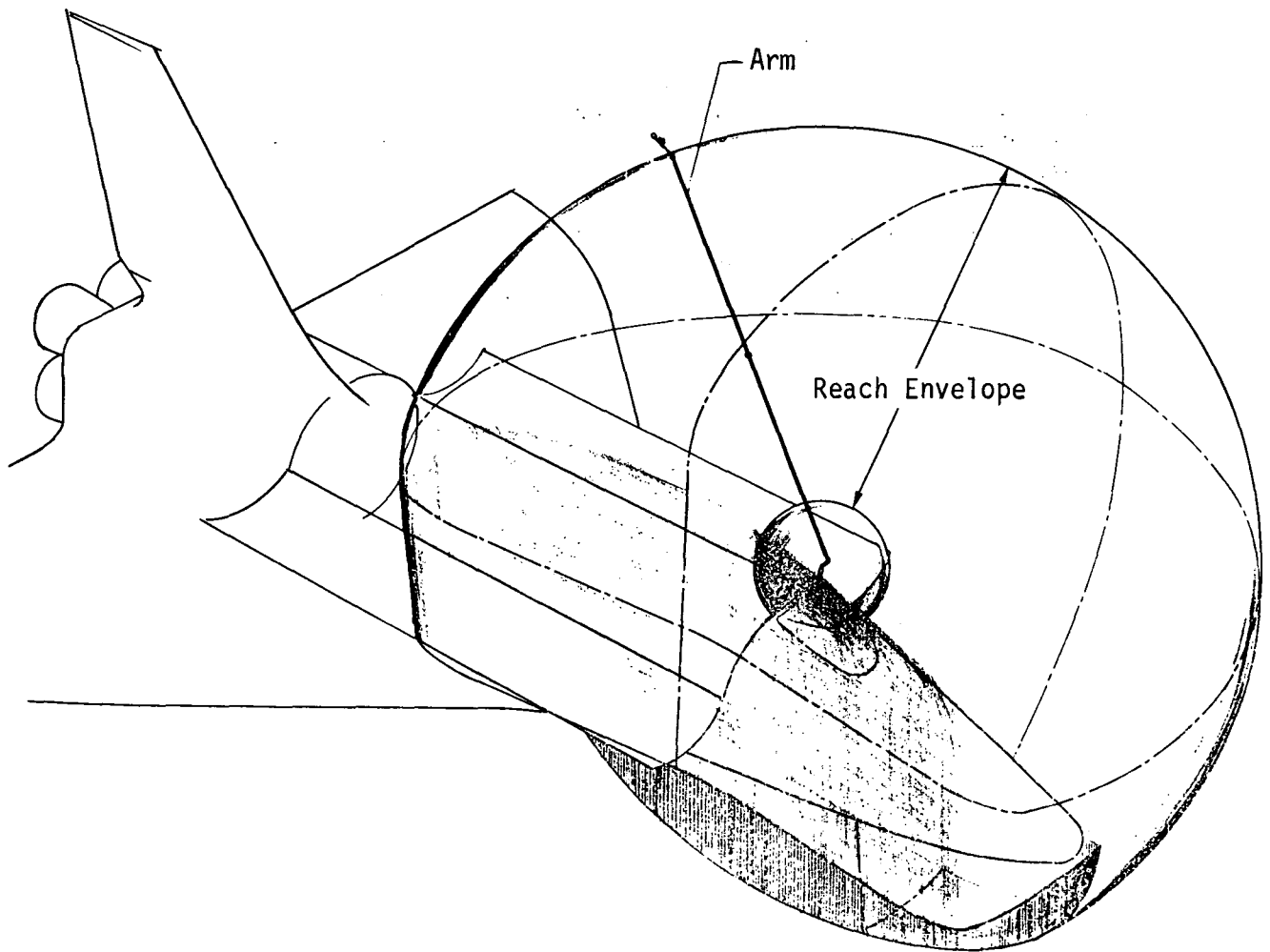


Fig. VII-2 RMS Reach Envelope - One Arm

B. CONTROL METHODS

Various control techniques for the RMS were considered, ranging from unilateral joystick control, with and without computer augmentation, to various bilateral control systems, utilizing both master/slave and joystick configurations. The number of possible alternatives was reduced to two, either of which provide the required sensitivity for fine manipulations as well as providing for gross movements of the large manipulator arms. A description of these two control systems is given in the following paragraphs.

Variable Ratio Mixed-Mode Bilateral Master-Slave - The basic difficulty with a normal master/slave control system is the disparity of the requirements for scale factors that are different for displacement and its first two derivatives. It has been established that sufficient no-load linear velocity capability must exist at

the master controller to prevent the operator from pushing too hard and saturating force reflection. A 14.3 m (47 ft) long slave arm might typically be controlled by a master scaled down by a factor of 1:18. If a 1:1 ratio is maintained for all angular displacements and the maximum linear velocity of the slave is 0.46 m/sec (1.5 ft/sec), then the maximum master velocity becomes approximately 0.025 m/sec (1 in./sec). This slow velocity appears much more like an isometric control stick than a master/slave controller. Force reflection will likely be at least partially saturated, so that for initial approach, the system is in a mixed mode; bilateral master/slave wrist plus a high ratio (essentially rate control) for control of the wrist point x, y, and z. Close to the target, the angular slave/master displacement ratio is changed by the operator from 1:1 to about 1:18, (for a smaller 0.79 m (2.6 ft) master), resulting in a true bilateral master/slave mode. This system allows gross movements of the slave to be accomplished with small motion of the master arm, and also provides the necessary sensitivity for final alignment and capture.

Bilateral Rate Control - One basic problem associated with all master/slave control systems is the requirement for additional space in the Shuttle cockpit to accommodate the master controller. To overcome this problem, a control system utilizing a six degree of freedom (or two three degree of freedom) bilateral joystick type handcontroller could be employed. This control system would operate in a normal rate command fashion, with the additional feature of force-feedback capability to allow the operator to feel the resisting forces and moments placed on the manipulator arm. The force feedback capability overcomes the problems associated with backdiving a unilateral rate control system, and also aids in attachment of the terminal device to the target. This system would employ multiple sensitivities for accomplishment of gross positioning as well as fine manipulations. The force-feedback capability could also be switched off for those tasks where it was not required. One problem associated with this system is that a force-feedback hand controller has not been developed.

C. TELECOMMUNICATIONS

The telecommunications subsystem provides the primary interfaces between the astronaut operator, the manipulator arms and the Shuttle. This subsystem must, therefore, have very high reliability. Hence, the tradeoff analyses are predicated on simplicity and reliability, except where an alternative method offers *significantly* better noise immunity, lower weight, or less power consumption. Tradeoffs and

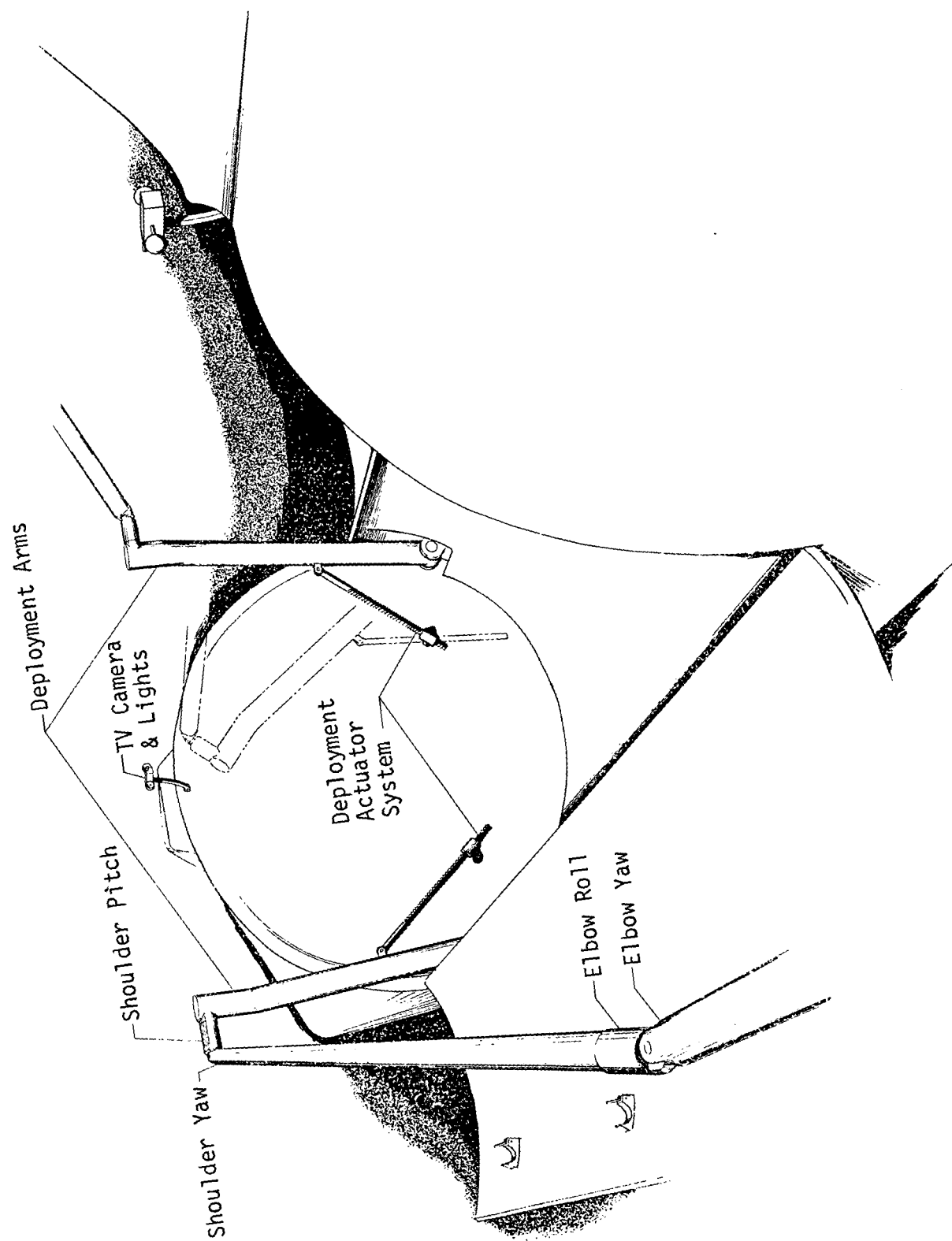
analyses were conducted in those areas that have a major impact on the preliminary design of the telecommunications subsystem. It is possible to relay command and data information between the manipulator arm and the control and data electronics either by an RF link or by cables. This option was considered and it was concluded that cable connections are preferable to an RF link. There is no requirement for auxiliary ranging or tracking and this requirement will not be included in the preliminary design. The relative merits of multiplexing arm data to reduce cable size versus direct simple cabling were determined. The conclusions favors simple cabling. Computation of servo command signals and others may be performed either locally at the manipulator arm joints or remotely in the control and data electronics. It was determined that there is no advantage to local computation.

D. DEPLOYMENT METHOD

Several deployment alternatives were reviewed, and the concept shown in Fig. VII-3 was selected for the preliminary design. Some of the criteria in favor of this concept are:

- 1) Easily meets a reasonable stowed position;
- 2) Deploys to a 6.1 m (20 ft) spread, clear of the top of the Shuttle, to provide adequate reach envelope and cargo clearance;
- 3) Can be made structurally adequate;
- 4) Has features amenable to ejection device if necessary in an abort;
- 5) Minimized actuator mechanism envelope requirements between cargo and cargo bay forward bulkhead;
- 6) Relatively light weight.

Details of the actuation mechanism for deployment can be varied. Although not included in this preliminary design, the mechanism selected is a screw jack device (with locks, stops, etc) as shown in the figure. Here either the nut may be driven on a fixed ball screw or the screw may be driven on a fixed nut. The former is preferable from the standpoint of drive motor with wiring, fixed to the bulkhead.



VII-7

Fig. VII-3 Remote Manipulator System Selected Deployment Concept

VIII. PRELIMINARY DESIGN AND ANALYSIS

The preliminary design and analysis was conducted in each of the five basic subsystem areas; Control, Structures, Mechanical, Crew Systems and Man-Machine Interface, and Telecommunications. The results indicate that the RMS is feasible, practical, and within current state-of-the-art.

A. CONTROL

The preliminary design of a master/slave force reflecting servosystem was accomplished. This system was selected over hand-controller approach for analysis purposes since it places somewhat higher logic requirements on the control system to accomplish the indexing and coordinate transformation necessary to allow full volume motion coverage of the large manipulator arm using a small master controller. Special attention was given to: (1) design and analysis of the servo control for the shoulder joint, (2) computer augmentation for the master/slave system when the two arms are operating in a nondirect angle tracking mode, and (3) discussion and examples of the coordinate transformations needed for operation in different coordinate axis systems.

A position-position force reflecting system was selected for the shoulder joint, and was analyzed from the transfer function matrix view point and the conditions on the system gains were developed for the master slave operation to meet the required performance criteria. It was shown that the gains must change as the arms are transferred from a 1:1 to an 18:1 angle tracking mode. The servosystem was programmed on an analog computer and runs were made simulating the response of the shoulder joint for a representative set of system gains, with input torques applied at both the master and the slave. It was shown that the servosystem investigated has a damping ratio of $\delta = 0.68$ and a damped natural frequency of $\omega_d = 0.88$ rad/sec.

The computer augmentation needed for the master slave system was determined, along with the manner in which the computer will interact with the servo control. The functions performed by the computer include coordinate transformations, adjustment of the

system gains, position indexing for full volume motion coverage, and the provision of control commands for preprogrammed operations.

B. STRUCTURES

It was shown that by proper distribution of the structural material of the arms important weight savings are possible, within the deflection and size constraints imposed on the manipulator arms. An optimizing procedure was developed to distribute the mass and stiffness among the sections of the arm to minimize the total weight for a 2.54 cm (1 in.) tip deflection under the design loading conditions, and with a constraint of 20.32 cm (8 in.) maximum diameter placed on the arm from shoulder to wrist. The conclusion was reached that considerable latitude is possible in the distribution of material without changing the total structural weight much from a nominal value of 453.5 kg (1000 lb). Because of the relatively heavy structure required to keep the tip deflection down to 2.54 cm (1.0 in.) stresses are negligibly low. A brief analysis is made comparing the baseline material, aluminum, to Lockalloy and boron epoxy. The results show a 70% decrease in weight if Lockalloy were used for the beam material. Frequencies associated with several of the more important possible modes of vibration are calculated under simplifying assumptions to permit preliminary comparison to control system or other disturbances.

C. MECHANICAL

The manipulator arm joints were analyzed for strength and component selection to fulfill the requirements of torque, speed, and acceleration. Joints were designed to provide reliable, safe operation with a minimum of ground maintenance for multiple launch usage and seven-day Shuttle missions. Nitrogen pressurized joints were incorporated for reliability and good heat transfer. Each joint is designed to contain 2 DC torque motors, a brake, tachometer generator, gearing and harmonic drive, potentiometer, limit switches, bearings, shafts, etc. to produce required outputs. Full-scale preliminary mechanical design drawings of each of the arm joints were made. The mechanical design guidelines are listed below.

- 1) Extrapolate from proven design;
- 2) Minimize differences between left and right hand arms;
- 3) Conservative Preliminary Design;
- 4) Aluminum arms;
- 5) Minimize backlash;
- 6) Consideration to be given for space hardware qualification requirements;
- 7) Major drive components operate in N_2 ;
- 8) Yoke-type joints for $\leq \pm 155^\circ$ rotation;
- 9) Spread bearings to decrease deflection, minimize loads;
- 10) Use dual motors for redundancy;
- 11) Use tachometer generators and potentiometers for rates and position.

Table VIII-1 presents a summary of the major joint components in the preliminary design. The selection of these components, gear ratios, etc. was made after performing a preliminary design analysis to assure conformity with the systems criteria. These components are not space-qualified; however, consideration has been given to this aspect in their selection to allow adequate envelope and functional relationship between components. A drawing of the elbow yaw joint is shown in Fig. VIII-1. This type of drawing was made for each of the joints.

D. CREW SYSTEMS AND MAN/MACHINE INTERFACE

A preliminary task/systems analysis was conducted for the activation and operational sequences of RMS use, as related to the Shuttle and Space Station. A detailed task analysis was performed for the capture/docking and cargo transfer tasks, since these tasks include most of the subfunctions of each of the other operational sequences. The required crew station volume was defined for the bilateral master/slave system, since the movement envelope of the masters dictates a larger volume than that required for the hand controller system. This additional volume is approximately 0.06 to 0.08 cubic meters (2-3 cubic ft). A control console was

Table VIII-1 Summary of Joint Components and Sizes

Column A Joint	Column B Type	Column C Motion	Column D Motor	Column E Approximate Gear Ratio	Column F Brake	Column G Potentiometer	Column H Limit Switches	Column I Tach Gen	Remarks
<u>Shoulder</u>									
1) Pitch	Overhand Cantilever Outward from Shuttle	$\pm 200^\circ$	2 Inland* T-1342.	Gears - 6:1 + 4.7:1 HD - 200:1 (4M) [†] (Total Ratio - 5670:1)	Simplatrol Model PMB-43 (Simplatia Corp)	CIC Multiple Turn or Stack of 2 to Obtain $\pm 200^\circ$ (Computer Instrument Corp)	2 Herm Sealed Microswitches.	Mag Tech. 1500C- 038 (Mag- netic Technol- ogy Corp)	Put D, E, F, I in 5 psi N ₂ Can Seal Output (2 rms) Shaft with 2 Viton Shaft Seals
2) Yaw	Yoke	$\pm 130^\circ$	Same as above	Same as 1)	Same as above	CIC 205 or Equiv (Only 240° Rqd)	Same as 1)	Same as 1)	Same as 1)
<u>Elbow</u>									
3) Roll	Rotary	$\pm 200^\circ$	Same as above	Gears - 3.88:1 + 3.88:1 HD - 200:1 (4M) (Total Ratio: 3000:1)	Same as above	CIC Multiple Turn or Stack of 2 to Obtain $\pm 200^\circ$. Wiper to Be Mounted On Output Shaft.	Same as 1)	Same as 1)	Same, Except Arrangement. Change to Roll/ Rotary Can.
4) Yaw	Yoke	$\pm 155^\circ$	Same as above	Same as 3)	Same as above	CIC 205 or Equivalent (Only 310° Rqd)	Same as 1)	Same as 1)	Same as 1)
<u>Wrist</u>									
5) Yaw	Yoke	$\pm 120^\circ$	Same as above	Gears - 3:1 + 2.5:1 HD - 200:1 (2M) (Total Ratio - 1500:1)	Simplatrol PMB 33 or Equiv	CIC 205 or Equivalent (Only 240° Rqd)	Same as 1)	Same as 1)	Same as 1)
6) Pitch	Yoke	$\pm 120^\circ$	Same	Same as 5)	Same as 5)	Same as 5)	Same as 1)	Same as 1)	Same as 1)
7) Roll	Rotary	$\pm 200^\circ$	2 Inland T-1352	Same as 5)	Same as 5)	Same as 3)	Same as 1)	Same as 1)	Same as Elbow Roll 3)
<u>Note:</u> All gear ratios may be changed (without changing overall ratio) to facilitate design layout fitting.								*Inland Motor Company [†] United Shoe Machinery Corporation	

VIII-5

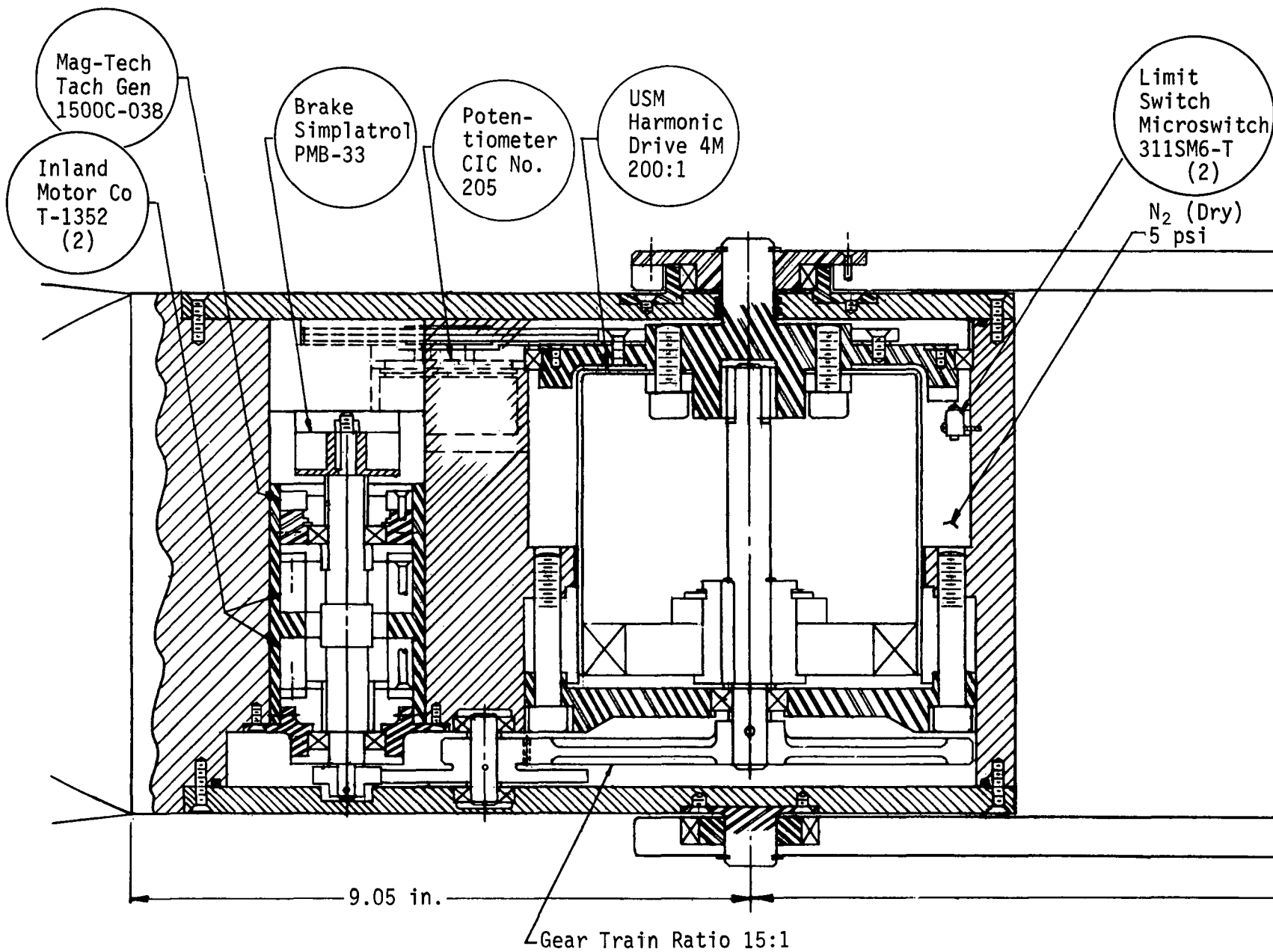


Fig. VIII-1 Elbow Yaw Joint

designed to provide the controls and displays necessary to allow the RMS operator to perform the tasks defined in the prior analysis.

The control station layout was designed around the two master RMS controllers. These controllers are the dominant feature of the station and take up the most volume when in operation. A neutral position was selected for each controller and a movement volume worked out from that. Two-dimensional mockups were made to determine the movement arc of each master segment. Since the master controller movement extends below the operator's waist he must be in a semistanding position. The movement of the master controllers is limited mechanically so they cannot extend beyond their operational reach. This will eliminate the possibility of contact with the instrument panel or other station equipment. The astronaut is restrained by a small seat with a waist strap. His shoulders are not restrained and he is free to lean forward to reach the control console switches. The control console is located 26 to 30 inches from the astronaut's eye when his back is vertical. All toggle switches are guarded, and rotary switches and pushbuttons are recessed to prevent inadvertent activation. The control console layout is shown in Fig. VIII-2, and an artists concept of the RMS control station is shown in Fig. VIII-3. As shown in Fig. VIII-3, viewing for RMS operations is provided by direct viewing capability from the Shuttle cockpit, supplemented by four mono TV cameras. Any of the four TV cameras can be selected on any of the three TV monitors on the control console, to give tridundant backup for the indirect visual mode.

E. TELECOMMUNICATIONS

The Telecommunications Subsystem consists of all electronic and electrical interfaces between the RMS operator, the manipulator arms, Shuttle computer and the Shuttle-mounted RMS equipment. It consists not only of control and data signals but also television, lighting, and power. The Telecommunications Subsystem Functional Block Diagram is shown in Fig. VIII-4. It consists of four groups divided by dotted lines. The first, the manipulator arms, includes the motors, the potentiometers, and the tachometers for each joint, as well as the wrist visual sensor group which is a television camera and associated lighting. The second group is the cargo bay equipment containing two television cameras, one at the front and one at the rear of the cargo bay with floodlighting associated with each camera. A deployment apparatus is used for each slave

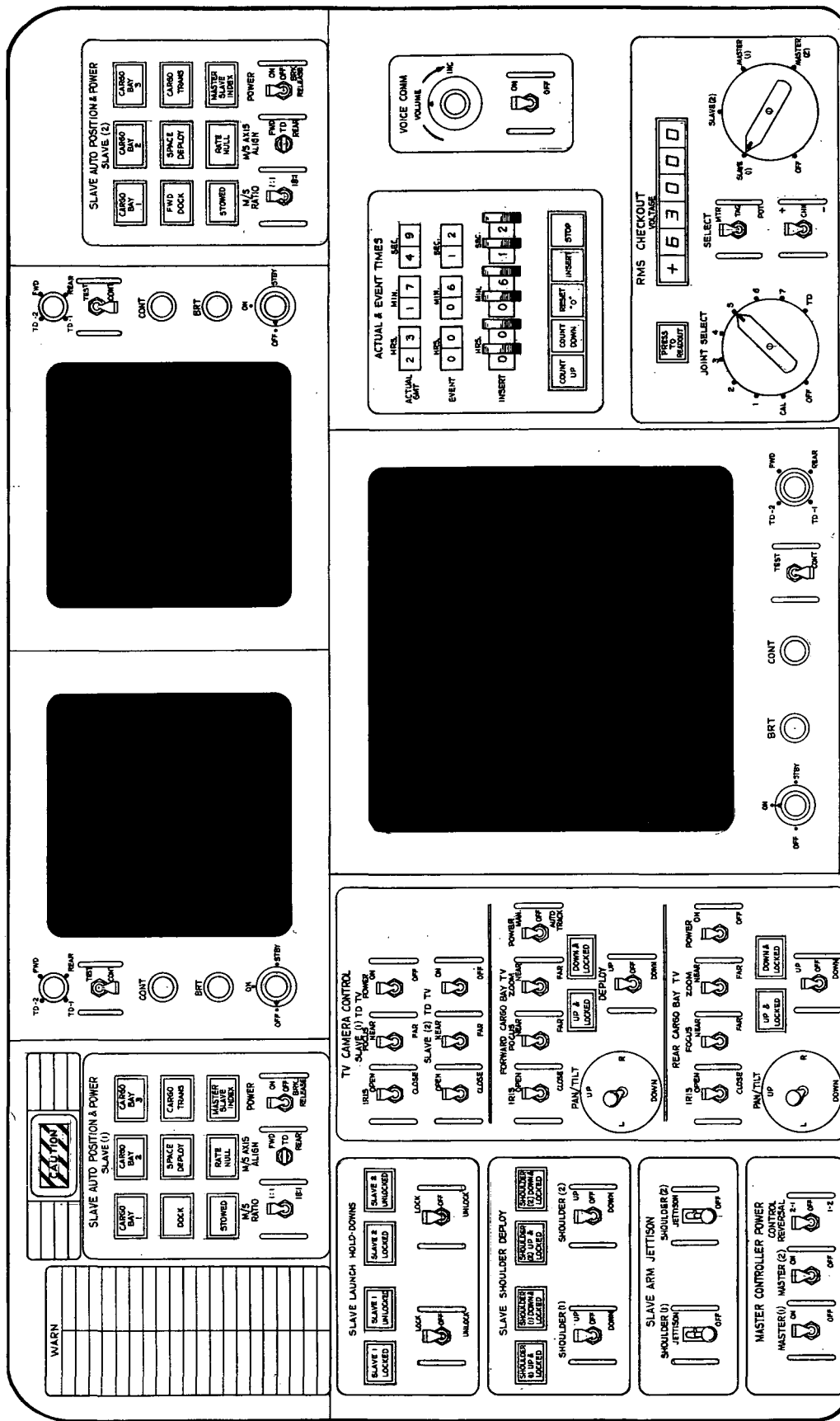


Fig. VIII-2 RMS Control Console Preliminary Design

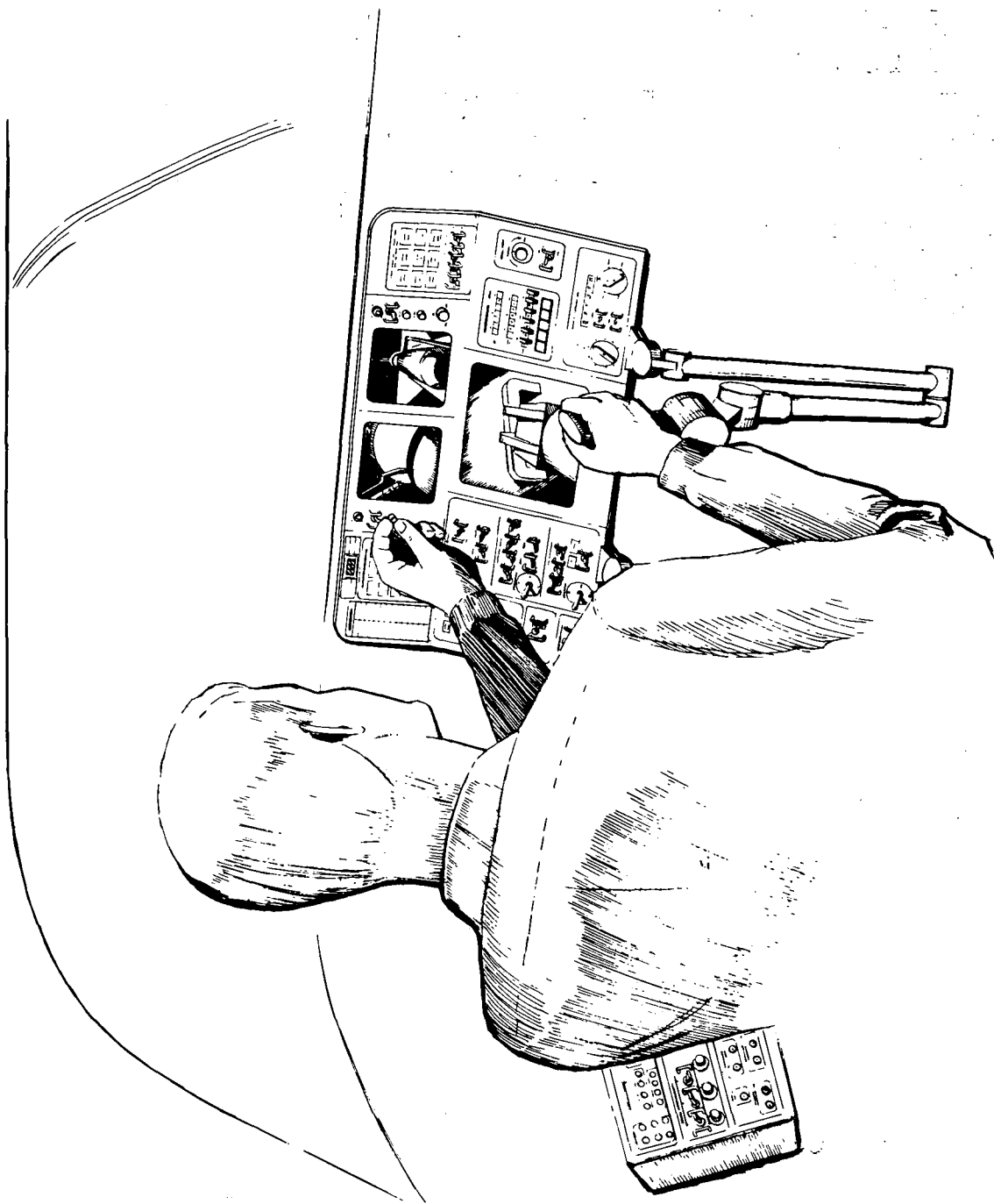


Fig. VIII-3 RMS Control Station

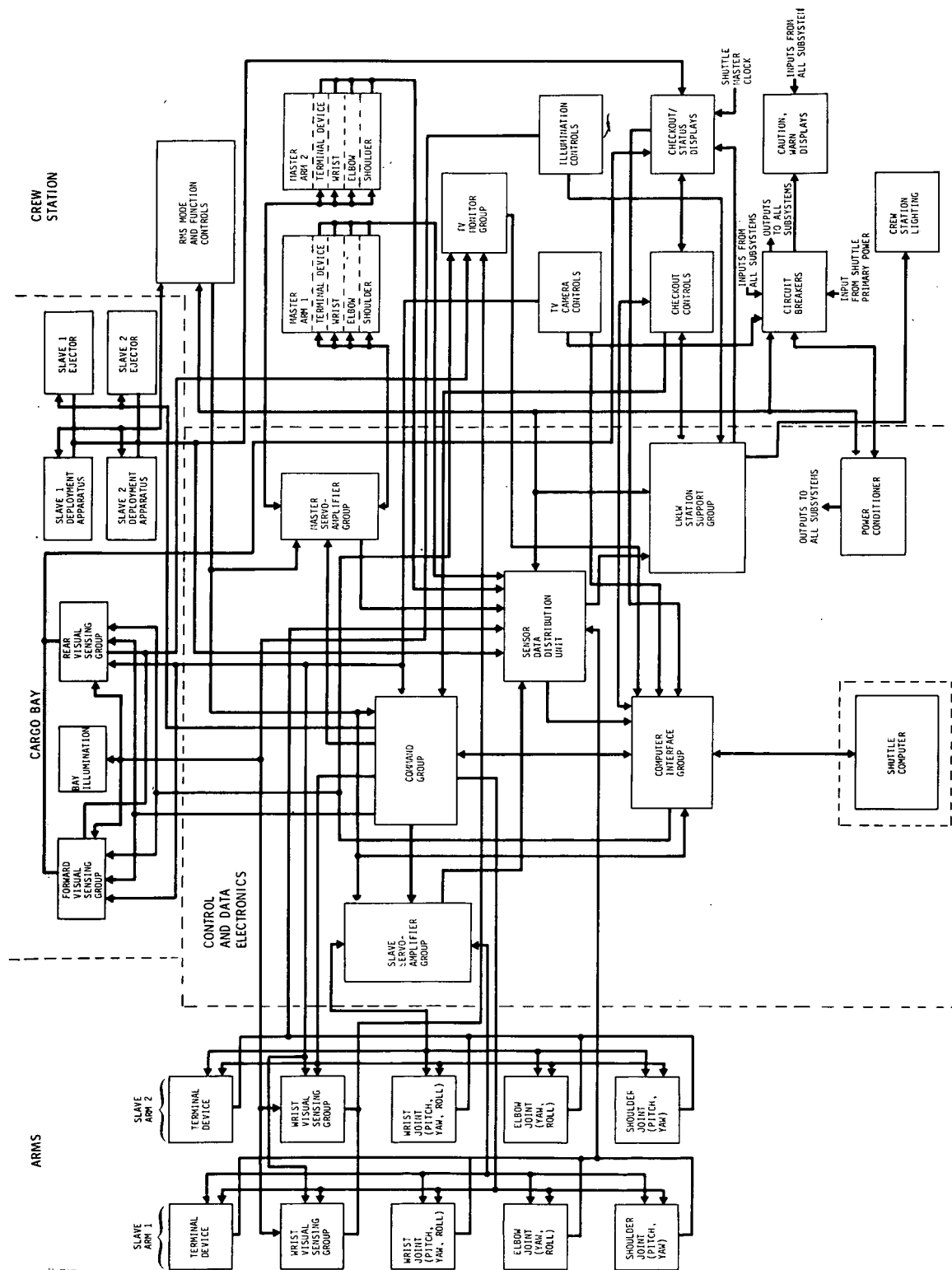


Fig. VIII-4 Telecommunications Subsystem Functional Block Diagram

arm to get it into and out of the launch configuration along with an ejector mechanism for each arm to jettison the arm in case of a malfunction.

The next group is the crew station. This consists of the RMS Mode and Functions Controls, the Arm Controllers, TV Monitor Group, TV camera controls, illumination controls, checkout controls, checkout and status displays, caution and warning displays, circuit breakers and lighting within the crew station. The Fourth Group is the Control and Data Electronics. This group is the heart of the Telecommunications System. It performs modification and distribution of signals and a small amount of computing. It involves the servo amplifiers, the signal distribution for command and sensor data, a computer interface group to interface with the Shuttle computer, a power conditioner, and a crew station support group.

Each block in the diagram was broken down to the point where all signal inputs and outputs are identified. The signals were identified by name, source, and destination, number of similar signals in the system, signal format, and signal activity. The signal activity refers to whether or not a signal is being used during various portions of the mission such as checkout, capture, docking, or cargo handling.

Various analyses and tradeoffs were conducted during the preliminary design. These dealt with parameters such as RF vs hardwire, multiplexing vs direct cabling, and TV camera selection. The watchwords during the tradeoffs were simplicity and available space proven hardware. Unless there was a significant savings in weight, power, envelope size, or some other critical parameter, we elected to go with the least complex or the most readily available. The results of these tradeoffs and analyses was a hardwired system with no multiplexing, and a TV system which could use the space qualified Apollo 15 LRV camera. The Preliminary Design utilizes only components that are available today. A practical telecommunications subsystem can be constructed entirely from existing hardware without the inherent risk of dependence on state-of-the-art development.

IX. FUTURE DEVELOPMENT PROGRAM

This chapter includes a typical development schedule and a budgetary estimate of the resources to design, develop, and manufacture the RMS for the Shuttle Orbiter. In order to accomplish this task, those activities normally associated with this type of a program were established. The schedule and cost estimates were then formulated from this data (Fig. IX-1).

Table IX-1 shows a breakdown of the estimates for manpower, material, computer, and travel for the RMS program. The estimate covers one qualification unit and one flight unit. Excluded from this estimate are a 1-g training unit, the terminal device(s), and postdelivery support.

Table IX-1 Estimated Resources

COST ELEMENTS		TASK																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
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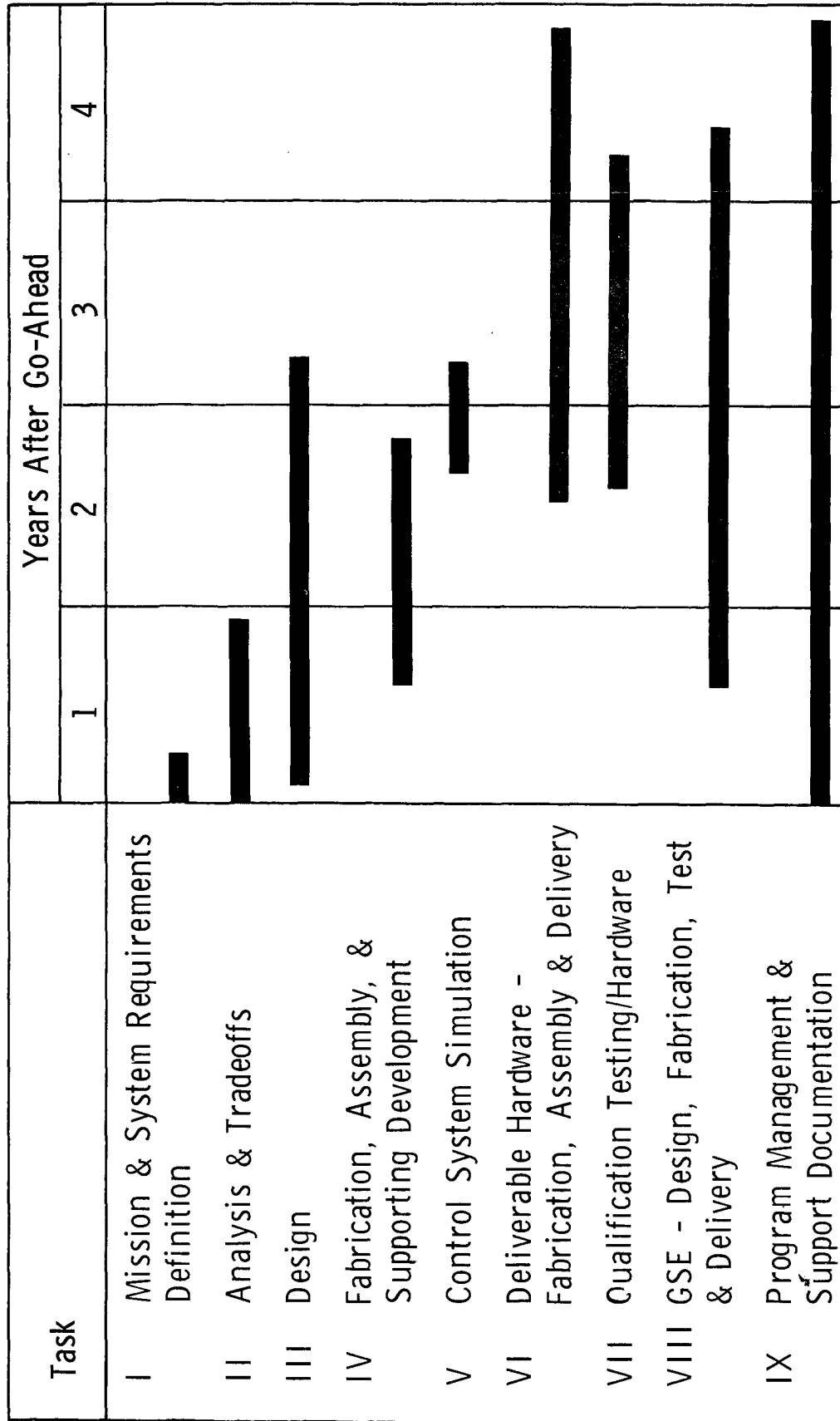


Fig. IX-1 Typical RMS Development Schedule

X. CONCLUSIONS

A preliminary design of a system for Shuttle docking and cargo handling has been completed. Analyses and design on the system and subsystem level show that no fundamental technical problems or restrictions exist; the RMS concept is feasible and practical. Our preliminarily designed RMS (1) can perform the required Shuttle tasks, (2) is compatible with the Shuttle Orbiter design, (3) has reasonable size and weight, and (4) has great operational flexibility and versatility. No technology development (advancement in the state-of-the-art) is required for future development.

A. SUMMARY OF SYSTEM SPECIFICATIONS

This section includes four tables: Table X-1, Joint Preliminary Design Characteristics Summary; Table X-2, RMS Preliminary Design Characteristics Summary; Table X-3, RMS Total Weight Summary; and Table X-4, RMS Electrical Power Estimate Summary;

Table X-1 Joint Preliminary Design Characteristics

	Shoulder		Elbow		Wrist		
	Pitch	Yaw	Roll	Yaw	Yaw	Pitch	Roll
1. Angular Travel (deg)	±200	±130	±200	±155	±120	±120	±200
2. Torque, N-m (ft-lb)	667 (500)	667 (500)	474 (350)	474 (350)	202 (150)	202 (150)	88 (65)
3. No Load Velocity (rad/sec)	0.03	0.03	0.0565	0.0565	0.174	0.174	0.174
4. Full Load Velocity (rad/sec)	0.0035	0.0035	0.0066	0.0066	0.0265	0.0265	0.0265
5. Position Accuracy (deg)	±0.113	±0.113	±0.113	±0.113	±0.113	±0.113	±0.113
6. Rate Accuracy (deg/sec)	±0.033	±0.033	±0.033	±0.033	±0.033	±0.033	±0.033

Table X-2 RMS Preliminary Design Characteristics Summary

1. Arm Length	Upper, 7.16 (23.5 ft); Lower, 7.16 m (23.5 ft); Wrist Extension, 0.9 m (3 ft); Total, 15.25 m (50 ft)
2. Deployment Mechanism	Diameter, 30.5 cm (12 in.); Wall thickness 1.27 cm (0.5 in.); Weight, 118 kg (261 lb)
3. Upper Arm	Diameter 20.3 cm (8 in.); Wall Thickness, 2.0 cm (0.78 in.); Weight, 229 kg (505 lb)
4. Lower Arm	Diameter, 20.3 cm (8 in.); Wall Thickness, 0.8 cm (0.31 in.); Weight, 97 kg (214 lb)
5. Wrist Extension	Diameter, 10.1 cm (4 in.); Wall Thickness, 0.8 cm (0.31 in.); Weight, 6 kg (13 lb)
6. Arm Stowage Volume	Diameter, 0.2 m (8 in.); length, 15.3 m (50 ft); Inside Cargo Bay
7. Control and Display Panel Size	0.66 x 0.84 m (26 x 33 in.)
8. Crew Operating Location	Shuttle Crew Cabin
9. Deployment	At Forward Cargo Bay Bulkhead; Swing Out with 6.0 m (20 ft) Separation Distance
10. Maximum Cargo Handling Capability	29,600 kg (65,000 lb)
11. Baseline Structural Material	Aluminum
12. Total Weight of RMS (Aluminum Arms)	1263.6 kg (2783 lb)
13. Total Weight of RMS (Lockalloy Arms)	619.3 kg (1364 lb)
14. Weight of Arms and Deployment Mechanisms	1135 kg (2500 lb)
15. Degrees of Freedom	Shoulder - 2; Elbow - 2; Wrist - 3; TD - 1; Total - 8
16. Gimbal Order	Shoulder - Pitch, Yaw; Elbow - Roll, Yaw; Wrist - Yaw, Pitch, Roll
17. Joint Sensors	Angular Position; Angular Rate
18. Tip Acceleration	No Load - Stop in 0.46 m (1.5 ft) from maximum velocity Full Load - Stop in 4.6 m (15 ft) from maximum velocity
19. Tip Position Accuracy	±0.051 m (±2 in.)
20. Full Load Tip Deflection	0.025 m (1 in.)
21. Arm Natural Frequency (First Fundamental)	0.53 Hz (no-load); 0.035 Hz (Max Cargo Load); 2.3 Hz (Shuttle-to-Shuttle)
22. Servo System	Bilateral Force-Reflecting
23. Control Scheme	Variable Gain Control Augmented with Selected Pre- programmed Trajectories
24. Command and Data Link	Hardwire, Analog
25. Computation	Shuttle On-Board General Purpose Digital Computer
26. Viewing	Direct Viewing Supplemented by Remote Control TV - 1 on each Wrist (before Roll Joint), 1 at Front of Cargo Bay, 1 at Rear of Cargo Bay
27. External Lighting	Apollo Type, 2 per Camera

Table X-3 RMS Total Weight Summary

Quantity	RMS Equipment	Estimated Weight, kg (lb)
2	Manipulator Arm and Deployment Device	1101.0 (2424)
1	Control Console	64.9 (143)
1	Control and Data Electronics	17.2 (38)
1	Shuttle Surface Mounted Equipment	80.7 (178)
Total Weight of RMS		1263.8 (2783)*
*Total would become 619.3 kg (1364 lb) if Lockalloy substituted for aluminum for beams.		

Table X-4 RMS Electrical Power Estimate Summary

Electrical Equipment	Average Power (watts)					
	Checkout	Precapture	Capture	Dock	Unload and Deploy	Module Unload Transfer and Dock
Slave Servo System	200	200	200	150	300	300
Master Servo System	100	100	100	50	100	100
Control and Data Electronics	55	55	55	55	55	55
Deployment Mechanisms	15	15	0	0	0	0
Ejector Mechanisms	0	0	0	0	0	0
TV System	32	40	40	30	40	40
Lighting System	1	164	164	164	410	328
Displays	5	3	3	3	3	3
Power Conditioner	80	80	80	60	100	100
Total Power per Task (watts)	488	657	642	512	1008	926
Operational Time (min)	10	5	3	10	10	10
Total Energy per Task (w-hr)	81.3	54.8	32.1	85.3	168.0	154.3

B. FURTHER ANALYSIS AND TRADEOFFS REQUIRED

The design areas listed below include those areas (1) examined in this preliminary design which require further detail analysis, and (2) those areas which were beyond the scope of this preliminary work, but which should be examined before final design work.

- 1) Master slave force feedback servo design and simulation;
- 2) Dynamics computer analysis, six degrees of freedom including Orbital effect;
- 3) Gimbal lock, reach envelope;
- 4) Master arm design for limited space;
- 5) Arm structural material;
- 6) Vibration, damping, and deflection criteria;
- 7) Sun, shadows, glare and lighting;
- 8) Visual cues for two dimensional TV;
- 9) Mono TV with force feedback simulation;
- 10) Functional task timeline analyses;
- 11) Terminal device requirements and design;
- 12) Launch pad test techniques;
- 13) Collision avoidance methods;
- 14) Arms as sensors simulation;
- 15) Computer augmentation software;
- 16) Joystick vs Articulated Controller (Master).

The design areas that follow should be worked as part of the final design.

- 1) Internal vs external arm stowage;
- 2) Thermal control;
- 3) Actuators and gear reducers;
- 4) Reliability improvement;
- 5) Joint and structural design tradeoff for small diameter areas;
- 6) Failure mode analysis;
- 7) Deployment mechanism tradeoff;
- 8) Arm eject methods for abort;
- 9) Wire flexing in space;
- 10) Direct vision and/or TV viewing tradeoff.